Geological interpretations of the gravity field of

the western Midland Valley of Scotland

BY

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This work is dedicated to the memory
of my father.
Also to my mother, with out her inspiration
this work would never have been completed.

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SUMMARY

A review of the deeper geology of the Midland Valley of Scotland and results from previous geophysical studies are discussed and presented.

The principal new gravity coverage was in the area of the Lesmahagow Inlier. A regional Bouguer anomaly map of the western Midland valley and its environs was compiled, using existing data and carrying out surveys locally to fill gaps. The heterogenous existing data was reduced to give uniform reference to NGRN 73 and the IGF 67 formula.

The combined results were analysed by progressive stripping of the gravity components related to particular formations. Firstly thickness map of the supra-Hurlet sediments was prepared and its gravity effect calculated. Next, the thicknesses of the Clyde Plateau Lavas was calculated from the magnetic anomaly map of Great Britain (Sheet 11) with due allowance for the effects of intrusions, (particularly at Bathgate). The pseudo-gravity effect of this Lava model was then calculated.

Reduced Bouguer anomaly maps are obtained by subtracting the Bouguer anomaly components arising from

the supra-Hurlet sediments and the Lavas (plus associated intrusions) from the total gravity field values.

Residuals were then analysed on the assumption that their major sources were most probably (i) the structure of the major crustal layering and (ii) the variation of (residual) thickness of the Lower Old Red Sandstone. A range of interpretations, as well as a 'most probable' model, was obtained. Estimates of the 'crustal gravity component' were made (1) by fitting a best surface to the reduced gravity values and (2) by combining the Upper crustal gravity component as calculated for LISPB model, with McLean and Qureshi's estimate of the regional component.

The gravity anomaly residuals attributable to the Lower Old Red Sandstone component are discussed and geological interpretations made.

CHAPTER 1

1 INTRODUCTION

1.1 The regional geology (Fig. 1)

1.1.1 The Midland Valley of Scotland: In the Midland Valley of Scotland the principal structure is the Midland Valley graben. It is about 80 km wide, and stretches for more than 200 km across Scotland, and probably for the same distance into Ireland. the north-easterly extension of the graben is uncertain because it is obscured by Tertiary overstep in the North Sea. The general succession within the graben has been estimated as not less than 3.6 km of Upper Palaeozoic rocks (Old Red Sandstone, Carboniferous and Permian) (George, 1965) resting on not less than 2.6 km of Lower Palaeozoic (Ordovician and Silurian) rocks (Dewey, 1971, Fig.3).

The trend of the bounding faults appears to be controled by the anisotropy of the basement which was deformed during Caledonian orogenic movements (Dewey, 1971, 221). The graben block may already have been a structural unit by pre-Lower Old Red Sandstone times (*cf.* George, 1960, 48; McLean and Qureshi, 1966, 267).

The major subsidence of the graben block took place during Lower and Upper Silurian (Downtonian) time. Thick deposits of Lower Old Red Sandstone facies are present within the Midland Valley, and control on contemporaneous deposits by the Highland Boundary Fault and Southern Uplands Fault has been demonstrated by Bluck (1978, Fig. 20). In his synthesis of this geology (1978, 270 - 276) he considers that marked subsidence is a characteristic of the fault zones, rather than of the entire block (p. 272) but lacks definite proof of the existence of his model. The observed throws along both bounding faults are consistently down towards the Midland Valley side, and this phase of movement was complete before the deposition of Upper Old Red Sandstone started. Anderson, in an earlier interpretation (1951, 107), considered the fault movement to be post-Lower Old Red Sandstone, *i.e.* persistence over a much longer period is well supported by evidence. They appear to have a significant dip-slip component, as shown by subsidence, but Bluck (1978, 274) believes the entire zone, as distinct from individual fracture within the zone may be a major transcurrent fault.

Later post-Upper Old Red Sandstone movement (with movements which are at least in part post-Westphalian) along the Highland Boundary Fault and the Southern Uplands Fault is relatively minor, local, and reversed in throw with respect to the main phase of movement. A similar reversal is seen on the Straiton Fault. Elsewhere within the graben, the major NE / SW trending features, Kerse Loch Fault, Littlemill Fault, Dusk Water Fault, present in the western region of the graben clearly affect the development of the Scottish Carboniferous Lower Limestone and Passage Beds ('Scottish Milstone Grit') and they must have been persistently active during Lower Carboniferous time (Anderson, In Richey et al. , 1930; Goodlet, 1957).

The final, large-scale movements were completed at the end of Westphalian time. An unfaulted "Permian" (Stephanian ?) vent in the Kerse Loch Fault indicates that movements had ceased (at least at that locality) by the end of the Carboniferous period.

The development of the Midland Valley has been discussed by Kennedy (1958) and by George (1960). Its role as a graben, receiving detritus from the high-rank metamorphic Highlands and the low-rank metamorphic Southern Uplands during Devonian times, is clear (Dewey, 1971, 221; Bluck, 1978, 256).

Kennedy (1958) argued that its Ordovician /

Silurian history was that of a transitional zone between deformation in the Highlands and sedimentation in the Southern Uplands. This view pre-dated plate tectonic models.

A reconstruction of major crustal development in southern Scotland during Lower Palaeozoic times, within a framework of plate tectonic theory, led most authors (Dewey, 1971; Powell, 1971; Gunn, 1973; Philips _et al._ ,1976; McKerrow _et al._, 1977; Longman _et al._ ,1979; Lagios and Hipkin, 1979) to conclude that the region, or the Solway Firth immediately to the south of it, was the site of a crustal suture, and of the final remnants of the Iapetus (proto-Atlantic) Ocean which separated earlier North American and European plates. the important evidence had already been examined, long before the Theory of Plate Tectonics was formulated - _i.e._ the ophiolites, and the faunal assemblages of Girvan, (which are like those of North America, but different from those of the Lake District), and Williams (1962) had felt a need to invoke a mechanism of continental drift to explain his findings. Later work confirmed and strengthened this basic conclusion about a plate suture, and also offered answers to other major problems, for example to "why andesitic volcanicity persists in the Lower Old Red Sandstone, at a time when subduction might be expected to have ceased, with a locking of plates ?". Philips *et al.* (1976) provide a solution by dextrally shifting Scotland from the southwest where, in the terms of their oblique subduction model, subduction during Old Red Sandstone times had taken place.

Other apprent discrepancies between simple plate tectonic models and the known geology were not easily resolved, and led to differences of interpretation. Among the significant differences are the precise site of the suture, and the supposed role of the ophiolites (?) along the Highland Boundary Fault. Gunn (1973) proposed (on insubstantial grounds) that the Midland Valley was the site of the suture; and a more elaborate and better argued model of Longman *et al.* (1979) has the same basic feature. The balance of evidence (particularly the crustal structure defined by LISPB seismic-refraction experiment), and the balance of opinion, favour a suture to the south of the Southern Uplands Fault (see for example, McKerrow *et al.* 1977).

At this stage of investigation more evidence is needed before an appropriate plate tectonic model can be selected wih reasonable certainty, and be fitted with any precision to the Midland Valley. Application of the theory is not yet at a stage where all observed features can be explained, nor can hidden features be predicted.

The Old Red Sandstone sedimentary basins have a sedimentary strike and elongation parallel to the structural grain of the adjacent rocks (Bluck, 1978). In the Strathmore basin there was a time gap between the orogeny in the adjacent source rocks and the inception of the basin, so a similarity in the orientation of the growing basin and the structural orientation of the source gives a spurious impression of unity in the development of both. This similarity in orientation is brought about by the reactivation of an older fracture, the Highland Boundary Fault (Bluck, 1978, 274). In contrast, although faulting had a dominant influence on sedimentation in both Lower and Upper Old Red Sandstone, the type and degree of fault control was different in each case. The nature of the fault control is not well known for the Lower Old Red Sandstone of the so called southern (Lanark) basin (Bluck, 1978, 274).

1.1.2 The marginal faults

The Southern Uplands Fault

To the south-west of New Cumnock, the Southern Uplands Fault has a general trend of N. 55 and separates Lower Old Red Sandstone strata from the greywackes of the

Southern Uplands. The rapid attenuation of the Lower Old Red Sandstone conglomerates north-westwards from the fault, indicates that the Southern Uplands already existed at the time of their formation, and was probably bounded by a fault scarp. An earlier, Silurian history of movement of the fault is suggested by the contrasting developments, and degrees of deformation, of Lower Palaeozoic rocks on opposite sides of the fault, but the changes cannot be specifcally related to the fault-zone.

Further to the southwest, the Southern Uplands Fault has Upper Old Red Sandstone on its north-western downthrown side, before ending against an apparently minor fault trending N. 40. This fault is part of a NW / SE zone which affects the south Ayrshire Coalfield. The Southern Uplands Fault appears to trail into it, as though the zone were an ancient flaw. To the south-west of this N. 40 fault, the Southern Uplands Fault is overstepped by Lower Carboniferous strata, which thicken rapidly to the north-west.

A section (McLean, 1966, Fig. 9) interpreting a detailed gravity survey in terms of known geology, and assuming a limited continuity of stratigraphic pattern along the fault zone at New Cumnock, shows a pre-Upper Old Red Sandstone Southern Uplands Fault with approximately 0.6

km of Lower Old Red Sandstone strata on the downthrown, Midland Valley side, and a major fault scarp related to it with Upper Old Red Sandstone and Lower Carboniferous strata banked against it. The Carboniferous strata appear to suffer no major faulting, and movement along the fault zone is limited to a gentle monocline, for about 1 to 2 km along this part of the fault zone.

On the south-western side of the N. 40 zone, the Southern Uplands Fault zone appears to persist as the Glen App Fault. At its extreme north-eastern end, this fracture is offset locally by 2 km from the projection of the Southern Uplands Fault, but swings in trend to the southwest (from N. 40) to roughly a line with the Southern Uplands Fault. Its throw increases markedly across a NW / SE fault, bounding the NW / SE zone already mentioned, to bring Upper Carboniferous strata against Lower Palaeozoic greywackes.

The Highland Boundary Fault

The Highland Boundary Fault is a wide zone of displacement which includes two or more major faults and monoclinal flexuring. Along most of its length, Dalradian (Lower Palaeozoic) rocks are present on its northwestern side, and Lower Old Red Sandstone on its southern side. Near Loch Lomond, however, Upper Old Red Sandstone is seen to overstep the southern fault, and to be thrown to the northwest, in a partial reversal of the 'pre-Upper old Red sandstone' displacement. To the southwest, in the Inverkip Gap near Greenock (Qureshi, 1970, 490), this same southern branch of the Highland Boundary Fault is covered by Lower Carboniferous rocks. These Clyde Plateau Lavas have, however, suffered only minor, discontinuous faulting. Further southwest in Arran, Upper Old Red Sandstone and Carboniferous strata overstep the entire fault zone, and are (as near Loch Lomond) downthrown to the northwest.

The Fault cannot be traced across the island (mainly because of the structural effects of the Northern granite) but a fracture at Dougrie on the west coast, is considered by most authors to be its prolongation. Its course across Kilbrannan Sound is more controversial, with the principal alternative explanations being (1) a southerly swing of course to pass through the channel between Sanda Island and the Mull of Galloway (and so stay concealed by water), before returning to its former trend and linking to a supposed continuation in Ireland (see for example, George, 1960, 55; Fig. 7), and (2) a persistent trend across to Kintyre where it crosses an area of poorly-exposed Dalradian rocks, and inferentially has only a small throw (McLean and Deegan, 1978, 106).

An important feature of the fault zone is the presence of serpentinites plus spilites and cherts of Lower Ordovician age. A supposed Mantle origin for the serpentinite led some older authors (see for example, Hess, 1955) to infer that the Highland Boundary Fault is a major reverse fault associated with an early Ordovician orogen belt ('tectonogene'), and some modern authors (see for example, Bluck , 1978 a) to see it as the plate tectonic equivalent, that is the site of obduction, and possibly of a plate suture.

1.1.3 The NE / SW faults

These faults are developed between Ardrossan and the Southern Uplands. The largest are the Inchgotrick Fault, the Dusk Water Fault, and the Kerse Loch Fault.

<u>The Inchgotrick Fault</u>

The central zone of the graben in the western Midland Valley is bounded by the Dusk Water Fault to the NW and the Inchgotrick Fault to the SE. Both display a similar swing of trend, in the case of the Inchgotrick

Fault from N 52 near the coast in central Ayrshire, to N 65 near Lesmahagow. At this eastern end there is a further, more rapid, change of trend to N 40 before it dies out, near Strathaven, against a minor ENE / WSW fault. Its continuation into the Firth of Clyde is difficult to follow, and is problematic (McLean and Deegan, 1978, 107).

Along much of its length in central Ayrshire, Upper Carboniferous rocks on the northern side are thrown down against Lower Old Red Sandstone, making the Inchgotrick Fault the most obvious, and apparently important, fault within the western graben. A sizeable part of this displacement is post-Westphalian, but there is evidence from changes of thickness of units in the Scottish Carboniferous Limestone Series that movement was taking place then. Near Symington the apparent throw of Limestone Coal Group across the fault as shown in the generalised section, is about 0.15 km, and the throw probably increases eastwards to a maximum of 0.25 km.

The Lower Limestone Group has a thickness of c. 0.012 km as recorded near East Doura Farm (6 km near Lesmahagow). Thicknesses of the Limestone Coal Group are about 0.06 km, while the Upper Limestone Group is c. 0.08 km as recorded from Caprington Bore on the north side of the fault. On the southern side of the fault (1.5 km south of Caprington Bore), the probable joint thickness of the Limestone Coal Group and the Upper Limestone Group is _c._ 0.05 km. Further south at East Doura Bore a joint thickness of the Limestone Coal Group and the Upper Limestone Group is _c._ 0.135 km as recorded on a six inch geological map, 23 SW. Compared with a joint thickness of the Limestone Coal Group and the Upper Limestone Group of _c._ 0.12 km on the northern side of the fault as recorded at Gauchalland Pit Bore (1.6 km south-west of Galston, (Richey _et al._, Figs. 22 and 24, 189).

The most dramatic stratigraphic change is the near-absence of Clyde Plateau Lavas on the southern side of the fault, compared with their apparently great thickness on the northern side. The precise decrease cannot be assessed from the known geology as the base of the Lavas is not exposed and the thickness on the northern side may be anything in the range of _c._ 1 km to a few tens of metres. A couple of flows occur locally on the southern side.

The gravity anomalies across the Inchgotrick Fault bear no simple relationship to the known geology (McLean, 1966) and the changes of gravity are much less than might be anticipated. An explanation can be found in terms of selecting a suitable thickness of dense Clyde Plateau Lavas on the downthrown, northern side - but this is only one of two geologically probable explanations. (p. 261-263).

The Dusk Water Fault

The particular fracture of this name is present in north Ayrshire, where it trends N. 40. The maximum throw between Ardrossan and Auchenmade of the top of the Clyde Plateau Lavas (mainly from magnetic evidence) was estimated by Park (1961) to be 0.3 km and this was supported by later seismic-reflection work (Hall, 1974).

The throw varies, however, with each horizon, as the successions on both sides of it differ. On the north side, the joint thickness of the Limestone Coal and Upper Limestone Groups vary from 0.16 km near Ardrossan to a maximum of 0.55 km near Pollockshaws. On the south side, the joint thickness is 0.16 km (Richey et al., 1930, Figs. 16 and 24).

The Dusk Water Fault, like the other major NE / SW faults within the western Midland Valley, was clearly active in Lower Carboniferous time, as well as having significant (final ?) movement in a post-Westphalian phase.

Although a fault of similar trend (N 40) persists north-eastwards almost as far as Paisley, and probably -

as the Paisley Ruck - as far as western Glasgow, the major displacement continuous with that of the Dusk Water Fault is along an ENE / WSW (N 60) fault (the Auchenmade Fault) which branches from it (Park, 1961). The change of thicknesses follows the same curving line (Richey et al., 1930). This apparent swing in trend of the main fault parallels a comparable swing of the Inchgotrick Fault.

The Dusk Water Fault dies away as a fracture before reaching the coast at Ardrossan (IGS Sheet 22) but the zone of fracturing is probably continued by another fault running parallel to it and about 1 km to the NW. A large fault of similar trend lies south-westwards in the eastern Firth of Clyde and forms a boundary of the Eastern Arran Trough, before apparently fading away near Arran. En echelon with it, is the major fracture detected geophysically in the Firth, the Plateau Fault, which can be traced as far as the North Channel. Where last seen it is aligned with the supposed "Highland Boundary Fault" in Ireland, and has a similar throw to the NW.

A puzzling feature of the Dusk Water Fault (in the strict sense) is the relationship between the observed gravity anomalies and the known geology and densities. They cannot be reconciled satisfactorily by invoking a simple step-fault model and concentrating all changes of succession across the fault at the step. There is a simple, but small, drop of anomaly value produced by the Carboniferous strata above the Lavas, but the gradients produced by deeper interfaces seem to be spread over a relatively wide zone, and their relation to the surface fault is not simple (McLean, 1966, 251). Their interpretation is complicated by the difficulty of distinguishing between thinning of Old Red Sandstone and thickening of Clyde Plateau Lavas.

<u>Kerse Loch Fault zone</u>

The principal elements of this zone are

(a) the Kerse Loch Fault, which runs south-westward from central Ayrshire to the north of the Dailly syncline and beyond that to the coast north of Girvan,

(b) the Littlemill Fault, which runs sub-parallel to this main fault and ends against it near Kerse Loch,

(c) an acute syncline formed in the down thrown block between these two faults (the Kerse Loch syncline),

(d) a "belt of steep metals" (<u>i.e.</u> a monocline with many minor faults), in which the disturbed strata are dipping at 60 or more and probably accompanied by at least one fault with a south-easterly downthrow (Simpson IN Eyles <u>et al.</u>, 1949), which occurs on the north-eastwards prolongation of the Kerse Loch Fault and Littlemill Fault, as the zone crosses the axis of the Mauchline Basin,

(e) a NE / SW fault extending from the "Belt of the Steep Metals" towards Muirkirk. The overall displacement across the entire zone is down to the south-east along its full length

The Dailly syncline bears a similar spatial relationship to the Kerse Loch Fault as the Kerse Loch Fault syncline, and they also may be structural elements belonging to the fault-zone. A possible genetic relationship between faults and synclines has been argued by McLean (1966, 250). If valid, the fault-zone has behaved essentially as a major fault during Carboniferous time.

Fault movements controlling contemporaneous sedimentation, characteristic of the major NE / SW of the western Midland Valley were first recognised along the Kerse Loch Fault zone. On the north side of the Fault, the combined thicknesses of the Carboniferous Limestone Series is of the order of 0.007 km at South Craig Bore. And less than 0.006 km of Millstone Grit on the south side of the Fault, at Houldsworth Colliery the thickness of the Carboniferous Limestone Series is only 0.055 km and that of the Millstone Grit is 0.02 km.

The Straiton Fault and The Headmark Fault

The Headmark Fault is considered to be a part of the smaller NE / SW trending faults present in central Ayrshire, and is probably the north eastward continuation of Straiton Fault (MacGregor In Eyles et al., 1949, 17), the Drumgrange Fault and a number of subparallel faults with relatively small downthrow on the south western margins of Mauchline basin. It is trending at N 50 E / S 40 W, and changes its direction gently to N 60 E / S 30 W towards its eastern margins. It has 0.28 km throw at Branichan (Eyles et al., 1949).

The fault at Dalmellington brings Coal Measures against the Lower Old Red Sandstone and causes a displacement of the Lower Carboniferous strata of unknown thickness, all the Upper Old Red sandstone strata and part of the Lower Old red Sandstone (Simpson et al., 1932, 127).

1.2 History of resaerch

Research on the deeper geology of the Midland Valley, which is of relevance to the present study, consists firstly of a number of geophysical surveys (particularly gravity surveys), secondly of syntheses of the regional distribution and development of the deeper rock formations (such as the Lower Old Red Sandstone), and thirdly of the development of rifts (particularly within the theoretical framework of plate tectonics).

1.2.1 Previous geophysical studies

(a) Gravity surveys

(1) McLean (1961 a, 1961b and 1966) made a semi-detailed survey of Ayrshire and its environs including the Sanquhar Basin, with detailed traverses locally across the major NE / SW faults. A complementary survey of density-distribution (1961 b) based on samples from outcrops, mine-shaft surveys, and topographic effects (Nettleton method) indicated that the the two most important planes of density-contrast (additional to basement layering) in terms of explaining Bouguer anomalies across the entire region were as follows: 100 kg m^{-3} density contrast between Lower Old Red Sandstone and Lower Palaeozoic greywackes; and 180 kg m^{-3} density contrast between Carboniferous sediments and Clyde Plateau Lavas, although the relatively low-density Upper Old Red Sandstone and

Permian sandstones were locally significant. The dense intrusions of Carboniferous age also produced anomalies locally, and variations of thickness of Clyde Plateau Lavas appear to be the simplest explanation of the anomaly pattern in north Ayrshire (see p. 64).

(2) Qureshi (1961, 1970) made a semi-detailed survey in parts of the Midland Valley and the Grampian Highlands of Scotland, flanking the Highland Boundary Fault-zone between Callander and Cowal.

Combining results from both surveys, McLean and Qureshi (1966) inferred that when allowance is made for the contribution to the gravity anomalies of the light Upper Palaeozoic rocks within the graben, the adjusted values outline an accentuated high over the centre of the graben with a drop of 250 to 300 g.u. from the maximum to the northern limit of the area (i.e. towards the southern Highlands), with a corresponding drop to the south (i.e. towards the Southern Uplands). The most probable geological explanation of this, is a crustal thinning of about 5 km (with the absence of the thick Lower palaeozoic geosynclinal sequences of turbidites of the Southern Uplands).

(3) Cotton (1968) made a detailed survey in the Campsies and inferred that the Clyde Plateau Lavas range in thickness between 0.25 km at North Third, and 0.75 km

[NS 276.690]

at Strathblane. He also explained that the probable reason for the thickening of Lavas at Strathblane ,is the piling up of extrusives around the vents of the western Campsies.

(4) Powell (1978 a) made a detailed gravity study of the serpentinites and ophiolites of the Girvan area. He gave a probable distribution of these rocks but gave no final conclusions about their origin.

(5) Lagios and Hipkin (1979) made a semi-detailed coverage of the east and south-eastern parts of the Midland Valley. In their interpretation of the gravity anomalies in south-east parts, they inferred the presence of a concealed granite batholith under Tweeddale in the Southern Uplands.

(b) Other geophysical surveys

(7) Hall (1971, 1974) made seismic-reflection studies in north Ayrshire and Renfrewshire in order to

determine thickness variations in the Clyde Plateau Lavas. He arrived at the following conclusions:

(A) the Lavas probably form an original pile along a NW / SE line. And they thin away from the axis of the present outcrop

(B) the maximum likely thickness of the Lavas is 0.9 km.

(8) Gunn (1973) using existing aeromagnetic data, suggested that the Midland Valley is a "remnant" of the proto-Atlantic Ocean (Iapetus Ocean), with the Highland Boundary Fault and Southern Uplands Fault marking the position of diverging Benioff zones. Sediments eroded from the flanking continental areas of the Highlands and Southern Uplands rest directly on oceanic crust.

(9) Bamford <u>et al.</u> (1976, 1977) in the LISPB seismic-refraction experiment, which was designed mainly to study Lower Crustal and Upper Mantle structures inferred the following:

(a) in the eastern part of the Midland Valley (the seismic refraction line passes through Edinburgh) no significant thinning from Southern Uplands into Midland Valley occurs.

(b) the 6.4 km s^{-1} layer beneath the Caledonian Foreland apparenlty extends beneath the Caledonian Fold Belt into the Midland Valley, but may terminate at the

Southern Uplands Fault. In N.W. Scotland this layer has been identified by Smith and Bott (1975) as granulite-facies Lewisian basement rocks. Its depth varies between 6 and 12 km.

(c) to the south a layer of lower velocity (6.28 km s^{-1}) underlying the Lower Palaeozoic sequences at a depth of 8 to 14 km may represent a pre-Caledonian basement.

(10) Powell (1978) made a magnetic study along the LISPB seismic-refraction line, and inferred that any granulites under the Midland Valley are less magnetic than their counterpart in the NW Highlands.

1.2.2 Regional geological studies

(1) Graham and Upton (1978) analysed gneissic clasts collected from Carboniferous vents in two localities in the Midland Valley, and interpreted them as fragments of a gneiss complex. Mineral assemblages and textures are typical of granulite-facies metamorphism, and they are geochemically similar to Lewisian granulites.

They also inferred that these gneisses could have been derived from a a layer defined seismically by LISPB at 7 to 8 km depth, which is unconformably overlain by Ordovician and later rocks.

This basement complex may have been an area of positive relief in Late Precambrian and Early Palaeozoic times, and its existence provides an important constraint on plate tectonic models of the Lower Palaeozoic, most importantly it suggests that the Caledonian suture lies to the south of the Southern Uplands Fault.

(2) Longman et al., (1979) reported the presence of boulders of metaquartzite, amphibolite and sheared granite in the northerly derived Ordovician conglomerate - with southerly derived Silurian conglomerates of the southern Midland Valley of Scotland. They pointed that this evidence support the existence of Precambrian basement under the Midland Valley.

(3) Bluck (1978) provides a comprehensive description of the distribution, the sedimentological setting, and paleogeographic evolution of the Old Red Sandstone in the Midland Valley. His interpretation, however, is entirely based on the sedimentological aspects of the Old Red Sandstone basins seen in outcrops.

1.2.3 Studies on the development of rifts

Neugebauer (1978) and Neugebauer and Braner (1978) have described a mechanism of rift formation mechanism and invoked the gravitational potential produced by updoming to explain excess extension. A summary of the development of of rifting at successive stages of progressive uplift with corresponding stresses and effects according to their model is as follows:

(1) 1/6 of maximum uplift at 5 M.a. - This stage is marked by the beginning of failure at the central base of the crustal dome. Tension exists near the centre and enables rise of magma into the lower crust as anaxial intrusion. At the crest of the dome stresses are very low and only upwarping is visible at the surface.

(2) 1/3 of maximum uplift at 10 M.a. - High magnitude tension at central part of the dome throughout whole crust, with onset of volcanic activity likely. Tension causes failure in the lower crust and may activate existing pre-doming faults in the upper crust. This incipient volcanic activity is confined to the crest of the dome.

(3) 0.6 of maximum uplift at 20 M.a. - This is characterised by the formation of faults in upper crust due to the increasing uplift. Failure occurs at the crest for first time, with corresponding tension concentrated in the upper 10 km. The major faults along the lines of

future graben are probably formed at this stage. Higher frequency of volcanic activity.

(4) final stage at 30 M.a. - Continuation of previous trends, maximum shear stresses and tensions spread outwards from centre of the dome. Faulting steps towards the flanks of the dome and so does volcanic activity. Strains in upper crust, subsidence of graben proper begins, and volcanic activity reaches a maximum. (From the concentration of stresses in the upper 10 km of crust, it may be concluded that a graben at that stage does not extend to such depth (cf. Rhine graben).

(5) Further post-uplift development: If no additional uplift, stresses are relaxed by faulting and volcanic activity decreases, with mechanical conditions for sporadic volcanic activity with gas and ash predominant. If a subsequent phase of uplift at rift, then revival of stress-fields of (1) and (2), and renewed volcanic activity at crest of dome (e.g. Rhine graben about 30 M.a. after graben formed).

1.3 Aims of the present research

The exploration of deeper, and concealed, geology by gravity surveys has conventionally served for reconnaissance preceding seismic surveys and deep drilling which lead usually to firmer conclusions than are obtained from gravity alone. As an additional control on interpretation becomes available, however, further analysis can be made of, and new meaning read into, the gravity data, and it has this additional 'interactive' function as well. The prime aim of the present study was to explore the deeper geology of the western Midland Valley, in so far as it could be done from gravity data, with the existing geological control. This control is so limited that the study must be rated as essentially a reconnaissance with little possibility of firm conclusions being drawn. Nevertheless, the project seemed worthwhile as a guide to planning and interpreting coming seismic-refraction projects, and other investigations of the deeper geology.

More than one model and more than one geological interpretation would almost certainly emerge, but limits could be set to the possible interpretations, and a most probable solution suggested. Even if there remained doubt about what was present, it seemed probable that it would be possible to say more definitely what was not present, and so conceivably distinguish, between the contrasting models of the development of Lower Old Red Sandstone presented by George (1958) and Bluck (1978).

Since so much of the structural development of the western part of the graben in Upper Palaeozoic times consists of movement along the major NE / SW faults (p. 10-12) and produces abrupt changes of succession across them, a secondary aim was to probe the geometry of these faults (hade ? throw ? changes across them ?) so far as possible by detailed surveys across selected localities.

To achieve these general aims it was necessary, firstly as a data-base,

(1) to compile a gravity map of the region, in which all data were referred to the same base-levels and made uniform;

(2) to fill in gaps of coverage, particularly in the areas of the Lesmahagow Inlier, and the Strathaven Hills.

(3) to make detailed gravity and magnetic surveys. In selected areas on major NE /SW Faults. These were carried out at High Dyke farm, Blaelochhead farm and at Holms and Middle Croft farms.

Secondly, to analyse the total field, it was necessary

(1) to prepare and test suitable computer

programs, some of which were made available by Dr Powell (pers. comm.), and others were either corrected, modified or converted from existing publications (technical journals or theses).

(2) to digitise the topographic maps of most of the Midland Valley, so that they can be used in the Terrain Correction program.

Finally, to interpret the components of the gravity field it was necessary to

(1) calculate the pseudo-gravity effect of the Clyde Plateau Lavas (including Bathgate from the magnetic map of Great Britain (Sheet No. 11)

(2) calculate the gravity effect of the supra-Hurlet Limestone sediments

(3) analyse the residuals after these components were subtracted

(4) invert the residuals maps into density-models

(5) Ultimately these density-models were interpreted in conjunction with published work.

CHAPTER 2

2. THE GRAVITY DATA

2.1 The existing surveys

2.1.1 Base station network

The pre-1973 network

The oldest network of base stations linked by gravity-meter in the Midland Valley of Scotland, was part of a calibration line linking the pendulum stations at Cambridge, York, Newcastle Upon Tyne, Edinburgh and Aberdeen, which was established by Bullerwell (1952). This was subsequently incorporated in a national network covering most of Scotland, which was established mainly by Bullerwell and Phemister (pers. comm.) in the early 1950's as part of their reconnaissance gravity survey of Scotland. These data were never published in a journal by their authors but were available to later workers. Their bases were re-occupied, the links were re-evaluated, and the network was extended by establishing new bases in the course of later, more detailed gravity surveys. Most of these regional surveys were carried out by the Applied Geophysics Unit of IGS and its predecessor the Geological Survey, or by staff and students from the Department of Geology, University of Glasgow. The efforts of the latter were concentrated in the western part of the Midland Valley, and in the adjacent sea-areas. A revised, and expanded, evaluation of this older network in the western Midland Valley was made and published by McLean (1966). This showed that the largest error in Bullerwell and Phemister's values of bases lying to the west of the calibration line, was in the value for Port Glasgow base. This error was propagated by the use of the Port Glasgow base as the tie-in point on the mainland for marine surveys on the Scottish shelf and surveys of adjacent areas.

The problem and its resolution are discussed in McLean and Wren (1978). Other surveys in the western Midland Valley (Qureshi, 1961; Cotton, 1968; Inamdar, pers. comm; Powell, 1978), in general, embraced smaller areas and used the Bullerwell and Phemister's, and the IGS bases usually without re-linking them to the calibration line, or adding more than a few local bases for the convenience of detailed work. Details are given in the published results. For the purpose of these surveys an accurate value of absolute gravity was not important.

Occasional revision of the values accepted as best, relative to a Cambridge Pendulum House value of 9812650. g.u., was made by IGS, and these emphemeral values were used as reference data as the occasion arose. This had produced by the mid-1970's a number of surveys in the western Scotland not uniformly referred to the same framework of base station values. A regional gravity map compiled from these unamended data would have been distorted at the margins of survey areas by these small changes of datum.

__NGRN 73 network__

The International Association of Geodesy (IAG) recommended (Resolution No. 11, IUGG) at its 1971 meeting in Moscow that - further to the provisional correction of - 140 g.u. (14 mGal) to the Potsdam value adopted at the Lucerne General Assembly in 1967 (Resolution No. 22) - the International Gravity Standardization Net (IGS 71) which incorpoates this adjustment and gives gravity values with the same order of accuracy throughout its range, be adopted as a datum. At British national level these moves helped to encourage the necessary, complete revision of gravity station values in U.K., with the most notable outcome being the National Gravity Reference Net 1973

(NGRN 73) established by the OS and the IGS (Masson-Smith, Howell and Abernethy-Clark, 1974). Cambridge Pendulum House has a value of 9812539.2 g.u. with respect to this new Reference Net, that is its value is reduced by 110.8 g.u..

These new gravity bases are sited at Fundamental Bench Marks (FBMs). There are four within the area considered in this thesis, which could be used conveniently to link the older networks (to which all the observations had been referred) to this system of reference (NGRN 73). Details of their locations were kindly provided by the Chief Surveyor Control, Scottish Region, Ordnance Survey. The distribution of these FBMs used, relative to the older base station network, is shown in Fig. 4.

<u>Linking the older base station networks to NGRN 73</u>

The adjustment made to each set of older observed gravity values so that all data is uniformly referred to NGRN 73 was carried out in two stages. Firstly differences in <u>g</u> between the four NGRN 73 bases and thirteen neighbouring bases in the older network were determined by looping between pairs (one new, one old) of bases. A second independent measurment was made of those links in which the original showed high instrumental drift, but the repeated results checked within 0.1 g.u., that is within the precision of the meter.

At the second stage of establishing the new integrated network tied to NGRN 73, the thirteen new links were treated as extensions to the old network. All the links in the revised (and extended) network were re-computed and the closure errors re-distributed using the least square adjustment method described by Bacon (1972). The constraint imposed in the computer program was to keep the NGRN 73 values of the four fundamental stations unchanged. Closure errors and new values for each link (with the appropriate closure error correction) within the integrated network are shown in Fig. 4.

The largest error is 1.9 g.u., and the R.M.S. closure error is 0.1 g.u. with an S.D. of 0.47 g.u. for a single observation. The tabulated results (Table 2) indicate that the older base station values (McLean, 1966) are higher by an average of 115.6 g.u. with respect to NGRN 73 with an S.D. of 0.36 g.u.. This difference may be ascribed (with reference to NGRN 73 and assuming no error in it) to;

(1) A change in Cambridge Pendulum House value of - 110.8 g.u. with respect to NGRN 73,

(2) An error in the older network (in part a calibration

error) between Cambridge Pendulum House and this regional network in the western Midland Valley of Scotland of 4.8 g.u..

The final stage of the revision was to adjust the values of the local bases established by Qureshi during his survey of the Highland Boundary Border, By Cotton in his survey of the Campsies, and by IGS survey near Bathgate.

Qureshi's network is linked to bases A.56 and B.37 of the integrated network. The revised values of these were used as the constraint when re-distributing closure errors. The new values are given in Table 2. They show an average drop of 116.1 g.u. from the older values with an S.D. of 0.36 g.u..

Cotton's local network is linked to bases A.87 (Dennyloanhead) and A.56 (Anniesland). The new values of his bases, using the revised values of these as a constraint, are given in column 3 of Table 4. They are 2.6 g.u. smaller, with an S.D. of less than 0.1 g.u., with respect to the older (IGS) accepted values at the time of his suvey, and 2.2 g.u. too low with respect to the values of McLean's (1966) network.

The IGS network has two stations A.87 (Dennyloanhead) and A.76 (Airdrie) in the Bathgate area, incorporated into the network, and used for a local survey. Their older values were 116.6 g.u. higher than NGRN 73 values with an S.D. of 0.2 g.u..

El-Batroukh's survey is linked to the network only by base A.40, and its revised value indicates that his values were 113.2 g.u. too high.

These revised base station values of the integrated network are used in referring all the older surveys to NGRN 73.

2.1.2 Reduction of the Bouguer anomalies to conform to NGRN 73 and IGF 67

IGF 67

During the period when nearly all the gravity surveys in the western Midland Valley and Firth of Clyde region were carried out, and the results reduced to Bouguer anomalies, corrections for latitude were applied using IGF 1930, which if ϕ is latitude and g is the theoretical value of gravity at that latitude then

$$g = 9780490. (1 + 0.0052884 \sin^2 \phi - 0.0000059 \sin^2 2\phi)$$

Interpolated values, accurate to 0.1 g.u., can be derived using a simplified linear formula where a survey area is of the order of tens of minutes wide.

In 1967 the International Union of Geodesy and Geophysics (IUGG) resolved (Resolution 1 and 2) that IGF 1930 may continue to be used as a reference for current work where a change would be disadvantageous, but that the Reference Ellipsoid 1967 and the corresponding gravity formula (IGF 67) be adopted as the standard reference data.

The new datum was adopted by IGS, and other British geophysicists, and IGF 67 is used in the present revision of older data. And the IGF 67 is :

$$g = 9780318. (1 + 0.0053024 \sin^2 \phi - 0.0000059 \sin^2 2\phi) \text{ g.u.}$$

Reduction of Bouguer anomalies to conform to NGRN 73

The data used in compiling the regional map (Fig. 5) were made available, or published, as Bouguer anomalies corrected using IGF 1930 and referred to Cambridge Pendulum House (accepted value 9812650. g.u.) and the older network values, with the exception of the more recently acquired data of Hipkin (pers. comm.). to amend them to conform to NGRN 73 and IGF 67, (i) the difference between IGF 1930 and IGF 67 was calculated for each station, using the co-ordinates of each station to determine latitude, and added to the Bouguer anomaly. And (ii) the average differences between the old base station values and the NGRN 73 values was calculated for each network, and was subtracted from the Bouguer anomaly. These average values that were used for each set of data are shown in Table 2. Applied Geophysics Unit of IGS (pers. comm.) convert from the old base station network to the new by multiplying the old "Gravity to C.P.H." by 0.99941 to look after the calibration changes (at the calibration range) and then simply adding 9812539.2 g.u. to the new differences.

Carboniferous sediments	2540 kg m^{-3}
Clyde Plateau Lavas	2720 kg m^{-3}
Lower Old Red Sandstone	2650 kg m^{-3}
Ordovician greywackes	2720 kg m^{-3}

Table (1) densities of rocks used in the calculations.

The densities used for both the Bouguer reductions and for terrain corrections have been specified as averages for each 4 x 4 km square block on the National Grid. These are listed in the printouts from the program.

Both the station data sheets and printouts are lodged with the Department of Geology in the University of Glasgow. For fuller list see also McLean (1961 a), El-Batroukh (1975), Qureshi (1970).

station number	1966 original value (1) g.u	1966 recalc value (2) g.u.	NGRN73 new val (3) g.u.	diff. (1-3) (4) g.u.	diff. (1-2) (5) g.u.
25/A19	2970.5	2970.5	2965.7	4.8	0.0
20'	2858.1	2858.0	2853.2	4.9	0.0
32'	3099.3	3099.4	3094.6	4.7	-0.1
24	3167.9	3167.7	3162.9	5.0	0.2
25	3263.0	3262.6	3257.8	5.2	0.4
37'	3345.1	3344.0	3339.2	5.9	1.1
BOWLING		3305.1	3300.3		
56'		3304.3	3299.5		
55'	3034.4	3034.4	3029.6	4.8	0.0
36'	3269.2	3268.9	3264.1	5.1	0.3
65	2917.7	2918.1	2913.3	4.4	-0.4
75	3055.7	3055.8	3051.0	4.7	-0.1
85'	2810.3	2810.5	2805.7	4.6	-0.2
76'	3028.5	3028.0	3023.2	5.3	0.5
87'	3371.2	3372.8	3368.0	3.2	-1.6
96'	3126.6	3126.1	3121.3	5.3	0.5
LINLITHGOW		3320.3	3315.5		
95'	2746.2	2746.3	2741.5	4.7	-0.1
THANKERTTON		2696.1	2691.3		
84'	2757.6	2758.1	2753.3	4.3	-0.5
92'	2590.8	2591.4	2586.6	4.2	-0.6
36/A03	2717.8	2718.3	2713.5	4.3	-0.5
53'	2927.1	2927.6	2922.8	4.3	-0.5
72	2657.0	2657.4	2652.6	4.4	-0.4
52	2776.2	2776.5	2771.7	4.5	-0.3
61	2605.0	2605.2	2600.4	4.6	-0.2
71	2664.1	2664.5	2659.7	4.4	-0.4
40'	2565.8	2565.9	2561.1	4.7	-0.1
Ayr		2905.0	2900.2		
43	3102.9	3103.0	3098.2	4.7	-0.1
44	2919.4	2919.6	2914.8	4.6	-0.2
A 35	3150.9	3150.7	3145.9	5.0	0.2
B 35	3102.0	3101.9	3097.1	4.7	-0.1
74	2779.5	2780.0	2775.2	4.3	-0.5

Table (2) : Comparison of the values of the old base station network with the present NGRN 73 referenced network. column (1) represents the last figures values given by McLean (1966) for his base station network and are referenced to a Cambridge Pendulum House value of 9812650.0 g.u.. Column (2) represents revised values of the old network, obtained after the inclusion of the inclusion of the four fundamental stations of the NGRN 73 and station 56, where closure errors were recalculated and redistributed. Values are given relative to a Cambridge Pendulum House value of 9812650.0 g.u.. Column (3) represents the new values of the network relative to a Cambridge Pendulum House value of 9812539.2 g.u., which refers to the NGRN 73. Column (4) represents the difference in g.u. between the old base station values and the values of the newly expanded network when both values are calculated relative to Cambridge Pendulum House. Column (5) represents the difference between the original values and the recalculated values after the addition of the extra five stations to the old network. This difference is due to re-distributing closure errors, using a computer program in calculating them. Stations labeled with a hyphen (') are those stations which are directly connected to the fundamental gravity stations of the NGRN 73.

station	original	recalc.	new	fiffer.	difference
number	values	values	Nnce		
number	values	values	NGRN 73	(3-1)	(1-2)
	(1)	(2)	(3)	(4)	(5)
	g.u.	g.u.	g.u.	g.u.	g.u.
56	3304.3	3304.3	3299.5	4.8	0.0
B 37	3345.1	3344.0	3339.2	5.9	1.1
A 37	3333.0	3332.4	3327.6	5.4	0.6
38	3378.0	3377.1	3372.3	5.7	0.9
48	3383.3	3382.8	3378.0	5.3	0.5
58	3292.6	3292.3	3287.5	5.1	0.3
69	3445.0	3444.5	3439.7	5.3	0.5
67	3334.9	3334.1	3329.3	4.6	-0.2
50	3477.3	3476.6	3471.8	5.5	0.7
79	3465.7	3465.5	3460.7	5.0	0.2

Table (3) : Comparison of the local base station values established by Qureshi (1961) with the NGRN 73 base station network. Column (1) represents the values originally given by Qureshi, but reduced relative to a Cambridge Pendulum House value of 9812650.0 g.u.. Two stations are in common with the new network, they are stations 56 and B 37, the difference between these stations were used as a constraint, when recalculating the network values as given in column (2), these values are given relative to a Cambridge Pendulum House value of 9812650.0 g.u., while column (3) represents those values compatable with the NGRN 73 but reduced relative to C.P.H. value of 9812539.2 g.u.. Column (4) shows the effective difference due to calibration. Column (5) represents the difference between the published values of Qureshi and his values afteter re-distributing closure errors in his network, and using the difference between stations 56 and B 37 as constraint.

station number	original value g.u. (1)	recalc value g.u. (2)	NGRN73 new val g.u. (3)	diff. (1-3) g.u. (4)	diff. (1-2) g.u. (5)
DENNYLOANHEAD	3370.5	3372.8	3368.0	2.5	-2.3
STIRLING	3463.0	3460.4	3460.4	2.6	-2.2
CARRONBRIDGE	3106.0	3108.2	3103.4	2.6	-2.2
KILSYTH	3236.8	3239.0	3234.2	2.6	-2.2
MILTON	3331.7	3333.9	3329.1	2.6	-2.2
GLASGOW UNIV.	3276.3	3278.5	3273.7	2.6	-2.2
RENFREW	3334.1	3336.2	3331.4	2.7	-2.1
FINTRY	3307.4	3309.4	3304.6	2.6	-2.2
ANNIESLAND	3302.2	3304.3	3299.5	2.7	-2.1

Table (4) : Cotton's (1968) local base station network. Values given in column (1) are those originally used by him, they are reduced relative to a Cambridge Pendulum House value of 9812650.0 g.u., then by fixing the difference between Dennyloanhead and Anniesland stations, a new values were obtained to refer them to the newly accepted values, but still referred to C.P.H. value of 9812650.0 g.u. (column 2). Column (3) represents new values referenced to the NGRN 73 and reduced to C.P.H. value of 9812539.2 g.u.. Column (4) shows the actual differences between the original values and the NGRN 73 network. Column (5) shows the difference between original base station values and the revised distribution of the closure errors in that network.

Data :Author Locality	correcction to base values to to refer data to NGRN 73 (NGRN 73 value of bases used) minus(pre-73 value) in Gravity units
<u>TUSON</u> Arran Tuson (1958)	-115.6
<u>McLean</u> Ayrshire and environs McLean (1961, 1966)	-115.6
<u>MANSFIELD AND KENNETT</u> Stranraer Basin Mansfield and Kennett (1963)	-113.2
<u>QURESHI</u> Highland Border Qureshi (1961,1970)	-116.1
<u>COTTON</u> Campsie Hills Cotton (1968)	-113.4
<u>McLEAN</u> Firth of Clyde McLean and Wren (1978)	-115.6
<u>POWELL</u> Area south of Girvan Powell (1978)	-115.6
<u>EL-BATROUKH</u> Southern Uplands around Loch Doon El-Batroukh (1975)	-113.2
<u>IGS</u> Area around Bathgate IGS (1966-1967)	-116.6
<u>AL-SALMAN</u> Lead Hills Al-Salman (1974)	-115.6
<u>LAGIOS AND HIPKIN</u> Eastern parts of the Midland Valley Lagios and Hipkin (pers.comm., 1979)	No corrections
<u>BOTT AND MASSON-SMITH</u> Criffell and Dumfries Bott and Masson-Smith (1960)	-113.2

PARSLOW AND RANDALL Cairnsmore of Fleet
Parslow and Randall (1973) -113.2

Table (5) Summary of the source data, area, and the correction used to update base values to conform to NGRN 73. **The 113.2 figures quoted above are derived from IGS station values.**

2.2 The new surveys

2.2.1 Description of the surveys

Additional surveys were carried out in those parts of the region, where the coverage of gravity stations was inadequate. The areas where only a few or no stations were present lay in the following 1/25000 Ordnance Survey maps; NN 50, NS 62; NS 63, NS 64, NS 71, NS 72, NS 73, NS 74, NS 92, NS 93, NS 94, and NS 53.

384 new stations were established to give an average density of 1 station per 3.2 km square over the region surveyed. Their locations are shown on Fig. 3. In addition to these semi-detailed surveys, detailed surveys were carried out at selected portions of the Inchgotrick Fault and the Dusk Water Fault.

Of the 316 new detailed stations established, 142 stations were at Blaelochhead farm near Lugton, 52 stations at Middle Croft farm and 88 stations at High Dyke farm on the Strathaven-Muirkirk Road. The locations of the traverses are shown on Fig. 3.

During the period of the surveys, the average drift of the Worden meter was 0.16 g.u. per hour. The heights of the observed stations were obtained from Bench Mark values on the published 6 inch or 1/25000 O.S. maps. Spot heights were used for 154 stations where levelling was impractical and no Bench Marks were available close to the station.

The observations (including the base stations used) and specific details of the reduction of these data to Bouguer anomalies are lodged in the Department of Geology, University of Glasgow, and will be deposited with Mr. Peter Howell of Applied Geophysics Unit of IGS.

2.2.2 Reduction of, and errors in, the new surveys

The new regional surveys

The new surveys were reduced to conform to NGRN 73 and to IGF 67. Bouguer corrections were calculated using the formation at the surface generalised on 4 x 4 km grid to represent the rocks between the station height and the datum, thus reducing the errors which would arise from the use of a uniform density over the whole survey area and integrating with terrain correction calculation using some gridded topography / density data. The density values used are those given by McLean (1961 b), and the density used for the 4 x 4 km grid block corresponding to each station is listed on the reduction sheets, or corresponding computer output.

In addition to the above standard reductions of the observations, corrections are made to all stations for terrain effects to Zone M. The average value of these corrections is 5.09 g.u., 30 stations have terrain effects exceeding 10 g.u., most of these are in the mountainous region of the Southern Uplands.

Errors in Bouguer anomalies of the new surveys

The errors in a Bouguer anomaly value with respect to the base station can be itemized as

(1) errors within the Base Station Network (Fig. 4) are described in page (33). The largest closure error is 1.9 g.u., and the R.M.S. closure error is 0.1 g.u. with an S.D. of 0.47 g.u.. These errors have been distributed among base stations.

(2) errors in observed gravity with respect to the base from which it was measured. A standard error of 0.7 g.u. has been calculated from 40 repeat readings at selected stations covering the area of the new survey.

(3) error of reduction;

(a) arising from an inexact determination of the coordinates of a station, and the corresponding value of theoretical gravity is not likely to exceed 0.1 g.u..

(b) arising from inexact determination of the elevation of a station, especially if there is no Bench Mark available i.e. the height is obtained from a spot height (given to nearest 15 cm) may produce an error upto 0.15 g.u.; while if there is Bench Mark the error is not likely to exceed 0.1 g.u..

(c) arising from an error in the near surface density value used to make the Bouguer correction, is the principal source of error in the Bouguer anomalies. For example an error of 20 kg m^{-3} in density will produce an error of 4.4 g.u. (for a station height of 0.518 km above datum which is the maximum station height in the surveyed area) in the Bouguer reduction, and hence in the Bouguer anomaly. This situation, however, is highly unlikely to arise, as errors of this magnitude in the formation densities are unlikely in the area surveyed.

(d) arising from making the terrain correction are likely to be 1.0 g.u..

The errors in a Bouguer anomaly value are, therefore, as follows with respect to NGRN 73 network:

standard error		
0.1	g.u.	theoretical gravity
0.15	g.u.	elevation correction error
1.00	g.u.	terrain correction error

The maximum likely error is 1.25 g.u. from above errors.
The probable error of the combination of above errors is 0.68 g.u.

The new local surveys across the NE / SW faults (see Fig.3 for location)

New detailed gravity (and magnetic) surveys were made at selected localities across the NE / SW faults mainly in the hope of pin-pointing changes of thickness of Clyde Plateau Lavas across them.

(a) At High Dyke, profiles were chosen across the outcrops of the Clyde Plateau Lavas and of the Upper Silurian of the Lesmahagow Inlier where geological control on interpretation is best. The Bouguer anomalies are rferred to Mean Sea Level at Newlyn. Latitude corrections are made using the linear formula

$$dg = 0.081 \sin(2\,Ø) \text{ g.u. per } 10 \text{ m} \quad \text{(N-S)};$$

and terrain corrections to individual stations are carried out to Zone G. near surface densities used for the reduction of the observed gravity readings are listed in the reduction sheets, (several density distributions were applied, in the attempt to achieve most likely densities for the near surface density).

The standard error for a tie between the local base and a station is 0.74 g.u. calculated from 14 repeats.

(b) At Holms and Middle Croft farms, Bouguer anomalies are referred to Mean Sea Level at Newlyn. Latitude corrections are made using the same linear formula in (a), and terrain corrections to individual stations are as in (a). Densities used for the reduction of the observed gravity readings are listed in the corresponding reduction sheets, and are obtained from the 4 x 4 km blocks used in the terrain correction program.

The standard error for a tie between the local base and a station is 0.65 g.u. calculated from 7 repeats.

(c) At Blaelochhead farm the Bouguer anomalies are referred to a local datum of <u>c.</u> 0.10 km (300 feet) above Mean Sea Level at Newlyn. Densities used for the reductions are 2730 kg m^{-3} for stations on the lava outcrop, and 2670 kg m for stations on the Lower Limestone Group outcrop. Latitude and Terrain corrections are as for (a).

The standard error for a tie between the local base and a station is 0.14 g.u. calculated from 19 repeats.

The results of these detailed surveys are not analysed fully as the original aims and approaches were modified as research proceeded. Values are incorporated into the regional maps, and for the sake of completeness they are mentioned here. The data are lodged in the Geology Department, University of Glasgow.

CHAPTER 3

3. ANALYSIS OF THE REGIONAL GRAVITY FIELD

3.1 The regional gravity map

The regional Bouguer anomaly map (Fig. 5) covers the western Midland Valley of Scotland, the Firth Of Clyde, the north-western fringe of the Southern Uplands and the border of the Highlands, around Loch Lomond.

The station density is on average 1 station per 2.7 km. The sources of the data are listed in Table 5 and the locations of individual surveys are shown on Fig.3.

The data are processed as described in section 2.1.2 reductions to Bouguer anomalies are of two type. In the first, the Bouguer anomaly values are obtained using an average near-surface density for Bouguer reduction and hence, an average elevation factor. In the second, the elevation factor has been varied to correspond to the actual density of the formation cropping out. In the south-western border of the Highlands, an elevation factor corresponding to an average density of 2670 $kg\ m^{-3}$ was employed to reduce the observed gravity to the Newlyn datum.

The probable error of a Bouguer anomaly is + 2.0 g.u. for most stations but for some stations on high ground, especially over the outcrops of the Upper Old Red Sandstone and the Clyde Plateau Lavas; it may be as high as 20.0 g.u. (Qureshi, 1970, 486) because of the error in near-surface density where an average is used. An elevation of 0.4 km above Newlyn datum of a station on Clyde Plateau Lavas (real density 2720 kg m^{-3}; assumed average 2670 kg m^{-3}) will produce an error in reduction of -8.4 g.u., and a station elevation of 0.1 km above Newlyn datum over the Upper Old Red Sandstone outcrops gives rise to an error in reduction of - 12.6 g.u.

In south Ayrshire and in the Lesmahagow Inlier, where there is a wide range of formation densities (McLean, 1961 a), the region is divided into areas corresponding to the main outcrops. An appropriate elevation factor is used for each (McLean, 1966, 243, 270). As the land in this region rises to over 0.3 km above Newlyn datum in places, the use of several discrete near-surface densities gives systematic errors of reduction at gently-dipping formation boundaries where the surface rocks do not extend down to sea-level. In the Bouguer anomaly map (Fig. 5) isogals are joined across the margins of these areas to give a representation equivalent to a continuous lateral change in the density of the rocks above O.D. Newlyn. The maximum error in a Bouguer anomaly in this part of the area, due to inaccuracy in determining the formation densities is at most 5 g.u. (on elevated stations in the Southern Uplands). Over most of the region it is much less.

Around Bathgate (Hossain, 1976) the Bouguer anomaly values are obtained by employing variable elevation factors corresponding to each block of area 4 x 4 km .

In the area of the Firth of Clyde, the Bouguer anomalies represent values corrected to Mean Sea Level (Newlyn datum), by replacing the water depths by material of density 2500 kg m^{-3}. The use of an infill density of 2500 kg m^{-3} may produce a spurious anomaly of up to 9 g.u., in extreme cases where either New Red Sandstone (density 2250 kg m^{-3}) or Lower Palaeozoic rocks (density 2720 kg m^{-3}) crop out over a wide area of the sea floor, and the station depth is at - 0.1 km (McLean and Wren, 1978, 9, 10).

In Arran the Bouguer anomaly values calculated by Tuson (1959) may be systematically 2.6 g.u. too low relative to the adjacent Firth of Clyde marine anomalies. The Arran survey was linked to Cambridge Pendulum House via the Kilmarnock base station (A 43) established By

Bullerwell and Phemister, and an older value was accepted.

3.1.1 The relationship of the Bouguer anomalies to the known geology

Comparison of the larger gravity anomalies with known geological structures shows

(i) a close relationship between high values of gravity and outcrops of Clyde Plateau Lavas in the Campsies and in Renfrewshire;

(ii) a close relationship between low values and the Carboniferous basins e.g. to the north of Bathgate (Stirlingshire Coalfield) and in South Ayrshire;

(iii) steep gradients towards the Upper Palaeozoic rocks of the Midland Valley across the Southern Uplands and Highland Boundary Faults;

The correlations are all consistent with the distribution of density determined by sampling formations (p. 38).

In contrast, major anomalies which cannot be explained by visible structures at the surface are

(a) a regional increase in values from the regions bounding the rift (southern Highlands and northern Southern Uplands) towards the axial zone;

(b) a near-circular high centred around Bathgate, that is on the eastern flank of a major Carboniferous synclines;

(c) a pronounced low near Hamilton (within the south-western part of the Central Coalfield), which has an amplitude significantly greater than can be attributed to the known thickness of Carboniferous rocks in the syncline;

(d) an area of low gradients between the Inchgotrick and Dusk Water Faults in north Ayrshire which bears no obvious relationship to the outcrops of the Kilmarnock basin.

The regional high (a) has been partially described by McLean and Qureshi (1966) who attributed its existence to the crustal structure of the graben and related crustal thinning (p. 278). Later surveys in the Southern Uplands (El-Batroukh, 1975) confirm and extend this pattern in western Scotland. Comparable regional gradients have been mapped by Lagios and Hipkin (1979), but interpreted as only partly due to crustal thinning. Their analysis is that the gradients are of a magnitude requiring an additional source - inferentially a granite pluton in the Southern Uplands Block. Recent results obtained by the LISPB (Bamford et al., 1977) seismic-refraction experiment have indicated the existence of crustal structure broadly similar to that inferred by McLean and Qureshi (1966).

The Bathgate high (b) was examined and analysed by Hossain (1976) who showed that this gravity high can be satisfied by two geological interpretations. The first is a block of Carboniferous basalts of thickness 4.5 km lying immediately under the Carboniferous Limestone Series. The Second interpretation is a deeper intrusion into the crystalline rocks of the Lower Crust with a density contrast of + 450 kg m^{-3} relative to the country-rocks. The density suggests ultra-basic composition.

The Hamilton low has never been fully analysed quantitatively, in terms of the gravity effects of known geology, and this is done later.

The distictive zone of low gradients in north Ayrshire (d) was discussed by McLean (1966, 261) who suggested that the most likely explanation for the lack of a marked fault step gradients across the Inchgotrick and Dusk Water Faults was that changes in anomaly value produced by the step in the strata are largely counter-balanced by variations in the thickness of Clyde Plateau Lavas. The evidence available did not, however, allow a firm conclusion to be drawn.

The major anomalies present in the Firth of Clyde region, have been described by McLean and Wren (1978).

They include a major high related to the Tertiary igneous Centre of Arran. Flanking lows to the north-east and south-west of Arran are interpreted as fault-bounded troughs infilled with New Red Sandstone. This interpretation is supported and confirmed by other work, including a seismic refraction survey, shallow seismic-reflection profiling, and boring. Geological control on interpretation of this sea-area is much less than is available in the rest of the region shown in the map (Fig. 5) and for that reason the Firth anomalies are not considered further in analysing the deeper structure of the graben.

3.2 Sources and components of the total gravity field

3.2.1 General disccussion

The International Gravity Formula 1967 gives values of the theoretical gravity st the surface of an ellipsoid formed of concentric density-shells. Any variation of structure in the real Earth from this horizontal density-layering would produce a gravity anomaly with respect to the values of IGF 67 at a station. Each and every structural anomaly with respect to horizontal layering affects the value of gravity, that is the magnitude of the gravity anomaly at the station. As a result, the major problem in interpreting gravity anomalies in terms of sub-surface structure is how to resolve the total anomaly into components, each related to a particular structure and the plane of density-contrast it deforms. If a logical basis for this resolution can be found, the next interpretational step of inverting the gravity anomaly to define structure is usually a comparatively straight-forward mathematical operation.

The principles and methods by which the total field may be resolved into components are

(i) harmonic analysis of the total field, combined with filtering and with theory which links, for example, the limiting depth of the gravitating source to some parameter such as the second vertical derivative of gravity.

(ii) surface fitting, where a polynomial of certain degree is calculated to be the best-fit surface to the total field. Only higher frequency components, produced by shallower sources remain as local anomalies after this surface is subtracted from the total field.

(iii) stripping the effects of known components from the total field, to leave one or more residual components. The known components are derived independently of the gravity survey, for example, from deep bores, from mining, from a geological survey, or from the interpretaion of sesmic, magnetic, or other geophysical surveys.

The first and to some extent the second, approaches to resolution, may be carried out with mathematical elegance, but are ineffectual in many real, complex cases. The contributions, or signals, from different interfaces may overlap in wave-length to an extent which makes the task of separating components from different depths incomplete, or even impossible. For example it would not be possible in the area studied to distinguish sharply on these criteria between anomalies emanating from the Moho, (which are produced by the crustal structure of the graben), and anomalies produced by regional changes of thickness of Old Red Sandstone within the graben.

The effectiveness of the third, and to some extent of the second method, depends on the availability of sufficient information about structure from other types of geophysical surveys or from geological sources. In practice the procedure may achieve no more than a simplification of the problem by removing the effects of the shallower layers, and limiting ambiguity in the interpretation to the nature of the deeper masses required to produce the residual field.

In the western Midland Valley intensive geological investigation, assisted by mining and some deep bore-holes provides fairly good geological knowledge of the strata as deep as the Hurlet Limestone horizon (See p.67), and satisfactory control for stripping the supra-Hurlet component. Below the Hurlet level, however, knowledge of the major formations is at best partial; even knowledge of regional changes of thicknesses. Any conclusions about the order of thickness of Old Red Sandstone (see, for eaxample, Bluck, 1978, 251-263) near the centre of the graben are based on observations near the margins, and on tentative paleogeographic reconstructions. The models of Old Red Sandstone development in the graben lack confirmation from other sources.

There is not sufficient supplementary data to determine the size of any of the sub-Hurlet horizon gravity components with accuracy; but enough to set reasoned limits to the regional form of deeper masses, and to offer a limited choice of density and geological models which may favour, or exclude, existing hypotheses. They may also offer a basis for designing seismic experiments, or for choosing critical sites for deeper borings.

The analysis of the total gravity field (Bouguer anomalies) which has been carried out rests on the premise that the most important sources of gravity anomalies from below the Hurlet horizon and within the region of Fig. 5 can be identified from known geology and formational densities, and are

(i) the major crustal discontinuities, (that is the surface between Lower Palaeozoic rocks and Upper Crust, and the surface between Upper and Lower Crust) (Fig. 2);

(ii) the unconformity separating Downtonian / Lower Devonian strata from denser Lower Palaeozoic greywackes;

(iii) the variation of thickness of the relatively dense Clyde Plateau Lavas and associated intrusions.

Local changes of thickness of the Calciferous Sandstone Series sediments, and of Upper Old Red Sandstone also contribute to the anomalies, but are likely to be of secondary importance, since the upper range of known thicknesses is 1.3 km , and the magnitude of the Bouguer anomaly associated with this is 54.5 g.u..

A more series complication would be the presence of any large igneous intrusions, particularly of basic composition, either into the Upper Palaeozoic strata or into the Lower Palaeozoic basement. Such an intrusion (Hossain, 1976) may be present under Bathgate.

Geological evidence of thicknesses of Clyde Plateau Lavas, and of Downtonian / Lower Devonian strata, is limited almost entirely to what is seen in outcrops. These are concentrated near the fringes of the region studied, and are sparse in its central area. Furthermore the outcrops often display only the top of the foramation and allow only a minimal thickness of the formation to be estimated. The only substantial source of supplementary information about the development of the Clyde Plateau Lavas is the IGS aeromagnetic survey (Bullerwell, 1968), and the results from it have been used - with awareness that other magnetic sources may confuse the interpretation - to estimate regional changes in thickness. Even less is known about the other two major sources of anomaly.

An estimate of the size of the deeper crustal component was, however, made along a selected line of section by McLean and Qureshi (1966). Their line of section is one where Upper Palaeozoic strata are relatively thin or absent. The regional anomaly curve along the line was a best-fit parabola to the gradients across thefringing southern Highlands and Southern Uplands (where Upper Palaeozoic are absent) and to points within the graben where tentative estimates of the Upper Palaeozoic cover's contribution to the gravity field can be made, and bestripped, from the total field. Their "regional anomaly" is the crustal component, (i) of page 63. Their interpretation of the derived regional gravity high as a thinning of the crust under the Midland Valley, was supported by the fragmentary geological evidence then available. Some confirmation came later from the LISPB seismic-refraction experiment (Bamford et al., 1977). Their interpretation shows a crustal structure across the graben in the eastern Midland Valley with similar features to McLean and Qureshi's model. There is however no direct check, or possibility of comparison since the LISPB line lies c. 40 km to the east of the region being discussed, but a comparable anomaly extends along then south-eastern margin of the graben (Lagios and Hipkin, 1979) and indicates a probable continuity of crustal structure along strike. This argument, and its apparent reinforcement of McLean and Qureshi's earlier conclusions, must, however, be qualified by the conclusion of Lagios and Hipkin, that the gradients across the margin of the graben iin the eastern Midland Valley cannot be satisfactorily explained purely by displacement of the crustal layers shown in the LISPB profile. They infer that the gradients are augmented by a large concealed granite mass in the Southern Uplands.

The Downtonian / Lower Devonian component of gravity cannot be estimated, even roughly, from independent information. Any conclusion about it must, at this stage of knowledge, rest on equating it with the residual values of gravity obtained after subtracting the two other major components from the total field.

Resolution of the Bouguer anomalies into these components is, therefore, an arbitrary and inexact procedure. The model obtained are likely to have a wide range of errors, and to demonstrate only the main qualitative features of the deeper structures. Nevertheless, at this stage of exploration of the deeper geology of the Midland Valley, the results serve as a guide in evaluating current hypotheses and in planning future investigations. The may not indicate with certainty what is present at depth, but can say with great assurance say what is not present.

3.2.2 The supra-Hurlet sediments component

Mapping supported by geological information from mining and quarrying gives a useable synthesis of stratigraphy and structure as deep as the Calciferous Sandstone Series in most of the Midland Valley. The most usefull and well-defined horizon, the Hurlet Limestone and its equivalents, was chosen as the base to calculate the thickness of the Upper sedimentary cover. A thickness map (Fig. 6) is constructed for the sediments between the Hurlet Limestone horizon and datum (Newlyn O.D.). The gravity effects (Fig. 7) of these sediments are computed assuming that they are to be replaced by strata having the density of Lower Old Red Sandstone rocks (density 2650 kg m^{-3})

3.2.3 The Carboniferous sediments below the Hurlet Limestone horizon

The Carboniferous rocks below the Hurlet Limestone horizon form the Calciferous Series, and are (MacGregor and MacGregor, 1948, 2nd ed. revised, 36)

Upper Group (with oil shales locally)

Volcanic Group

Cementstone Group

Too little is known about the development of the Upper

Group and the Cementstone Group to justify an attempt at systematic stripping of anomalies arising from them. Instead, the order of magnitude of the Bouguer anomalies likely to be produced by lateral changes of thickness in these strata, and the consequent errors in a derived model where residual anomalies are interpreted as variations of thickness of Lower Old Red Sandstone on a Lower Palaeozoic basement, are estimated.

Within the western Midland Valley, the upper Group varies in thickness from near-zero in north Ayrshire to 0.3 km in the Glasgow area. Corresponding changes in the Cementstone Group are from zero to 0.2 km. Since the Calciferous Sandstone sediments have a density contrast of -100 kg m^{-3} relative to the Lower Old Red Sandstone density, the total increase of thickness between north Ayrshire and the Glasgow district produces an anomaly of approximately -20 g.u., and a corresponding error in the residuals after (incomplete) stripping of Carboniferous gravity effects. This error in the Bouguer anomaly residual values would be misinterpreted by plotting the Lower Old Red Sandstone / basement boundary 0.72 km deeper than than its real depth.

Errors in the east-central part of the region, where outcrops of Calciferous Sandstone provide only partial information of the Series, may be larger. If the maximum known thickness - a total of 1.3 km in East Fife (more than 50 km the region analysed) - were, however, accepted as an upper limit of thickness, then the error arising from not stripping the Calciferous Sandstone sediments would be 54.5 g.u., and the error in the basement depth of the final model would be 1.85 km.

3.2.4 Estimation of Clyde Plateau Lavas thicknesses from aeromagnetic

Evidence from outcrops shows that the Clyde Plateau Lavas thickness varies from zero to several hundred meters, probably to a maximum of 1.0 km, across the Midland Valley (MacGregor and MacGregor, 1948, 2nd ed. revised, 36, 42). With a density contrast of 70 kg m^{-3} (2720 - 2650) their replacement by Lower Old Red Sandstone would give rise to a gravity effect ranging up to 40 g.u.. Their pattern of thickness and, consequently, related gravity variations cannot, however, be predicted from the geological evidence. The form of their lower surface is especially uncertain.

The distribution of anomalies on the IGS aeromagnetic map (sheet 11) of the Midland Valley shows a correlation with that of the Clyde Plateau Lavas outcrops. Over these outcrops the magnetic anomalies, measured at

0.3 km above them, commonly have amplitudes of 200 nT and 1/2 wave-length of 5 to 10 km. Tertiary dykes within the Clyde Plateau Lavas outcrop around Strathaven have magnetic effects which modify, but do not overwhelm, those attributable to the lavas themselves. Linear anomalies clearly follow the limits of the lavas where their edge is a topographic feature (Strathblane - Stirling NS [25 68] - NS [28 69] and near Largs NS [22 66]) or a fault (Inchgotrick NS [27 64] and NE of East Kilbride NS [26 65]). Beyond the Clyde Plateau Lavas, over the Old Red Sandstone outcrop, even where this is itself volcanic rock, the magnetic field is relatively uniform. The same is true where the Clyde Plateau Lavas are concealed by younger sediments despite sill and dyke intrusions. The Ayrshire basins are an exception due to the presence of younger basalts (Millstone Grit and Permian) and were excluded from further analysis.

The broad aeromagnetic high across the Central Coalfield syncline centred near Bathgate is taken to be due to a concealed intrusion subjacent and similarly polarised to any, also concealed, Clyde Plateau Lavas and therefore indistinguishable magnetically or, it is assumed gravitationally (Hossain, 1976). The Waterhead gravitating body unnder the Campsies (Cotton, 1968) produces the principal magnetic anomaly over that Clyde Plateau Lavas outcrop and is treated similarly below.

On the basis of these qualitative magnetic features related to the Clyde Plateau Lavas a quantitatve determination of lava thicknesses has been attempted. For this purpose a uniform polarisation of 3 x 4 pi x 10 Weber m^{-2} has been used. This is the figure arrived at by Cotton (1968) from susceptibility measurements on laboratory specimens from the Campsies and one which satisfies the observed amplitudes of the aeromagnetic anomalies over topographically defined edges to the lavas i.e. where the lavas geometry is known (Gargunnock NS [27 69], Largs NS [23 66]). It is also close to the intensity which minimises residuals in fitting a Clyde Plateau model to the anomalies along a 255 km National Grid N-S line (7th in Fig. 9).

The Clyde Plateau Lavas model for comparison with the observed anomalies was set up as follows:

1. The observed anomalies were sampled at 1 km intervals on 5 km spaced N-S lines across the area (Fig. 9 shows observed anomalies and profiles).

2. The zero datum was taken as that of the zero contour on the aeromagnetic map.

3. The elevations of all observation points (ground + 0.3 km) were recorded. Some lie below parts of the magnetic body.

4. The model comprised a series of 5 x 1 km vertical blocks centred under each observation point within the outcrop of the base of the Clyde Plateau lavas.

5. The depths to the top surfaces of all blocks were specified with reference to O.D. at Newlyn. Over the outcrop these depths are the average (over 5 x 1 km) ground height. Where the lavas are concealed the top depths equal ground height minus estimate of overlying Calciferous Sandstone thickness minus thickness of supra-Hurlet (thicknesses above as well as bellow O.D. are required throughout).

6. An initial set of base depths for iterative adjustment by the Calculating program was proposed. More than one initial set was used in attempts to minimise residuals between observed and calculated.

7. The pre-existing program was modified to allow for the differences in the elevations of the calculation point.

The best result (average residuals 32 nT) is shown in Fig. 14 (contours are the base below O.D.) Fig. 13 shows contours of the input depths to the top.

Clyde Plateau Lavas magnetic model

Fig. 14 shows the calculated depths to the base of the Clyde Plateau Lavas and associated intrusions where these are below O.D.. The calculated values have been smoothed by a 3-points running average along profiles (3 x 5 km blocks). The Lower Old Red Sandstone replacement gravity effect of the Clyde Plateau Lavas (density contrast 70 kg m^{-3}) has been calculated for this body where the top surface is truncated at O.D.. Its maximum effect over the Clyde Plateau Lavas is 32 g.u. and over the Bathgate body is 63 g.u..

The results are of direct geological interest in providing a picture of original Clyde Plateau Lavas thickness and its variation (Fig. 12 represents depth to base minus depth to top). No allowance is made for Calciferous Sandstone (Volcanic detritus). Although similar to Fig. 14, because most of the depth variation occurs at the base, Fig. 12 which corrects for post-Clyde Plateau Lavas differential subsidence, reveals a closer correlation between thickness and present Clyde Plateau Lavas outcrop. This indicates that the NW / SE Clyde Plateau Lavas outcrop through Strathaven into Renfrewshire particularly was the axis of maximum original accumulation.

Within that region the Dusk Water Fault line is the northern limit of the thickest lava development; presumably by contemporaneous movement. The thickest change approaching the Inchgotrick Fault line is more gradual. The NE trending fault bounding the Hamilton circular feature is less clearly related to the Clyde Plateau Lavas thickness contours. An older feature than the Clyde Plateau Lavas, either a Lower Old Red Sandstone basin or an acidic intrusion (see ch. 4) also shows a relationship to these faults.

Under the northern outcrops, the Clyde Plateau Lavas are relatively thin; less than 0.5 km under Kilpatrick Hills where an outcrop width and dip estimate is more than twice that figure. It may be significant that the line joining the centres of the Waterhead and bathgate intrusions parallels the Strathaven axis and a vent alignment in the Campsies.

Maximum thicknesses of c. 3 km under Bathgate being 3 times that of any geological estimate of lava thickness and explains the probability of an intrusive body.

At Waterhead the calculated thickness of c. 1.3 km; where base of lavas is geologically well controled at above O.D. thicknesses within the topography are c. 0.3 km, so similarly indicate an intrusion beneath Clyde Plateau Lavas.

Pseudo-gravity calculation of the Clyde Plateau Lavas and associated intrusions

For Clyde Plateau Lavas replacement density is 2650 minus 2720 km m^{-3}, the two intrusions, presumably gabroic, can be expected to be denser say 2800 - 2900 kg m^{-3} i.e. density contrast with Lower Old Red Sandstone upto 3 times that of Clyde Plateau Lavas. To apply differential density effect, the boundaries between intrusive and extrusive rocks are still to be defined. This may not be the main problem in applying a pseudo-gravity correction at Waterhead where on account of the relatively small scale of this feature, the shape and amplitude in observed gravity effect are not faithfully reproduced on map (Fig. 5). Similarly the 5 x 3 km blocks of the magnetic model are too big. For these reasons alone the the pseudo- and observed gravity are not a good match at any assumed density and application of the correction probably tends to create a spurios feature in the residual maps (Figs. 19, 20, 21) (shown by dotted isogals).

For Bathgate it is resonable to suppose that the intrusive effect far exceeds any Clyde Plateau Lavas effect, since the Clyde Plateau Lavas are thin (less than 0.5 km) under the area immediately to the west of this feature.

Two possibilities have been considered:

(1) density of the intrusion equal to that of the Clyde Plateau Lavas (contrast − 70 kg m^{-3}), not requiring separate defenition of the intrusion. This pseudo-gravity correction leaves a residual gravity high (D) on the site of the observed high separating residual Lows C and E.

(2) density of intrusion 2850 kg m^{-3} (contrast 200 kg m^{-3}) applied to all the magnetic model thicknesses East of [270]. This correction virtually compensates for the observed gravity high. So that, on the residual map (Fig. 20) Lows C and E tend to form a continuous feature.

3.2.5 The regional crustal component

Fig. 16 shows Bouguer anomalies in the Midland Valley and adjacent strips of the southern Highlands and Southern Uplands left after the supra-Hurlet sediments and the Clyde Plateau Lavas components have been subtracted from the total field

The 3rd order surface which fits best these values is shown on Fig. 17. In contrast with the profile derived by McLean and Qureshi (1966, 275, Fig. 2) the Old Red Sandstone component has not been isolated and subtracted from the values of the surface and the reference density of the surface is that of Lower Old Red Sandstone (2650 kg m^{-3}) instead of the Lower Palaeozoic rocks density of 2720 kg m^{-3}. The gravity anomalies shown on Fig. 17 are, therefore, composite in origin. The principal components areise from (1) the <u>regional</u> variation of Old Red Sandstone thicknesses within the Midland Valley, and (2) the deeper crustal structure. Any changes in the Old Red Sandstone which are random or local with respect to the graben and its bounding faults, are likely to be filtered out by this process of surface fitting. That is the gravity anomalies represented by the 3rd order surface values are related to a smoothed version of the structure of the major crustal layers, modified by a component which arises from regional thickening and thinning of the Old Red sandstone from the margin of the graben towards its axis. It is, however, of limited value for comparison with McLean and Qureshi's profile, or fo projecting that profile over the area considered. The large changes of thickness of Old Red Sandstone across the bounding faults are accommodated within it, since they are systematic with respect to the major graben structure. They flatten the high, and decrease the gradients over the margins radically, in comparison with the profile and the observed gradients across the Lower Palaeozoic outcrops. The surface serves for little other than to confirm that the high is a regional feature and trends NE / SW along the axis of the graben.

Neither the wavelengths nor the trends of the two principal components of the anomalies shown on Fig. 13 differ to a degree which offers a theoretical basis for resolving the cumulative anomalies into the two fractions, (1) and (2). The one possible difference which may be used is that the crustal structure related to the graben and the gravity component (2) associated with it, appear to extend beyond the bounding fualts across the southern Highlands and northern Southern Uplands, whereas the Old Red Sandstone effect does not. If it were assumed that the gradients associated with major crustal structure, seen in these bordering regions where Upper Palaeozoic rocks are absent, also extend with steadily decreasing magnitude into the Midland valley (cf. the crustal doming associated with graben elsewhere), then there is basis for an argument towards a most probable model. Otherwise it is only possible to proceed by considering the extreme possibilities that (a) the full magnitude of the regional anomaly arises from major cruastal boundaries - the Moho - and within the crust; or that (b) the changes are related to the Lower Old Red Sandstone regional component.

If the 3rd order surface (Fig. 17) were used as a simplified version of the anomalies shown on Fig. 19, then total Old Red Sandstone thicknesses would be obtained by adding local values found from the inspection of the residual anomaly map (Fig. 19) which was obtained after subtracting Fig. 17 from Fig. 16 along the area adjacent to the Southern Uplands Fault, and equating it to zero values of anomalies there.

Estimates of the crustal component from other sources

A resolution of the anomalies shown on Fig. 17 or on Fig. 16 could only be achieved if there were sufficient information, independent of the gravity results, about one or both components. Adequate control of this type on interpretation does not yet exist. A tentative model, the most probable at this stage of investigation of the Midland Valley, may be based, however, on estimates of the magnitude of the crustal component, made at two localities in the Midland Valley. The first is along the NW / SE profile chosen by McLean and Qureshi (1966), where Upper Palaeozoic strata are absent (at the Lesmahagow Inlier) or thin. The increased geological control compared with elsewhere in the graben allows a tentative stripping of the entire Upper Palaeozoic effect, including that of the Old Red Sandstone. the margin of error is wide, but it is unlikely (p. 254) that the order of magnitude of gradients, or the general argument, is wrong.

The second locality where the crustal-layering contribution to the gravity field of the Midland Valley can be estimated, is along the LISPB profile-line. Using the crustal structure as interpreted by Bamford and others (1977, 484) and assuming the following equivalencec of velocity - and density - layers, 6.0 km s^{-1} has a density of 2720 kg m^{-3}, and 6.4 km s^{-1} of 2800 kg m^{-3}, gives the gradients shown on Fig. 17. A gradient of 7.4 g.u. km at NS [53 65] dectreases to 1.4 g.u. km at NS [31 71]. These computed values are close in magnitude to the values derived by McLean and Qureshi, 70 km to the S.W. along that margin of the graben. There is consistency, and even if no firm conclusion can be drawn, encouragement to explore the possibility that the general character and magnitude of the crustal component is similar across the area investigated to that shown by McLean and Qureshi's curve.

<u>ADDENDUM.</u> The original construction of the regional component (Fig. 18) has errors of contouring near the axis of the high. The change of gradients produced by hand-contouring are inconsistent with a deeper crustal source. The revised version (Fig. 27) represents a lower order surface which is consistent with a source in the depth range 10 to 20 km, and with the presumed crustal-layering origin. The residuals from both (Figs. 21 and 28) arebasically alike and the stated conclusions (initially based on Fig. 21) are valid.

CHAPTER 4

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4. GEOLOGICAL INTERPRETATION OF THE FINAL RESIDUAL MAP

4.1 Description of the final residual anomalies

The residual Bouguer anomalies, obtained after subtracting from the total gravity field those components related to (i) supra-Hurlet sediments, (ii) Clyde Plateau Lavas (including the Bathgate pseudo-gravity effect) and (iii) major crustal layering, are shown on Fig. 21 and 28. These values ~~of component (iii)~~ are arguably (325) the best estimate, on current geological knowledge, of the contribution of the Lower Old Red Sandstone/Upper Silurian strata to the total Bouguer anomalies. The remaining complicating factors, additional to errors of reduction, are (i) any variations of thickness of the Lower Sedimentary Group of the Calciferous Series, and of the Upper Old Red Sandstone; and (ii) the possible presence of major intrusions, known neither known from near surface geology, nor from their magnetic effects.

The errors and problems of reduction have been discussed at each stage (p. 32-35). The major features visible on Fig. 21 are persistent qualitatively and are, with the exception of High D, independent of the probable errors in thicknesses or densitied used.

Any modification to Fig. 21, within the limits of geological probability, would have a scaling effect essentially, or would produce distortion of the major anomalies. They would not, however, destroy the dominant features of the map, nor produce additional major anomalies. The most important source of error, particularly in its effect on interpretation of Upper Silurian / Lower Old Red Sandstone regional thicknesses, is the estimate of the crustal component (iii) in the axial zone of the graben. Too large a gravity high, would produce a spurious excessive thickness of Lower Old Red Sandstone, and vice versa. To demonstrate this, and the range of interpretation possible, at this final stage of reduction, two sets of final residual anomalies are shown, discussed, and inverted to produce density-models. Each may be modified around Bathgate by choosing a higher density (2850 kg m^{-3}) for the pseudo-gravity effect of the intrusion, i.e. a density more appropriate for gabro The suffix 'a' identifies such modified Residuals.

The first Set of Residuals (Fig. 21; Fig. 20 shows Set 1a) is produced by subtracting a crustal component based on the results of McLean and Qureshi (1966) and LISPB. It is considered to be the most probable interpretation. It is not only the one which gives the most probable thicknesses of Upper Silurian /Lower Old Red Sandstone strata, but also the greatest thicknesses.

The second Set of Residuals (Fig. 19) is produced by subtracting a regional component equivalent to the averaged variations in Upper Silurian /Lower Old Red Sandstone effects, appro-ximated by the third order best fit surface (p. 77). The gradients of this surface and the maximum values in the axial zone of the graben are much lower than those used for the first set, and are used arbitrarly as a measure of the lower likely limit of strata thicknesses. The extreme (theoretical) lower limit (p. 78) is represented by the anomalies between the Highland Boundary Fault and the Southern Uplands Fault (Fig. 19) before a crustal component determined by inspection of the residual map is subtracted.

The major features recognisable in Residual Set 1 (Fig. 21) are

(1) relatively steep decreases of gravity near the marginal faults. These zones may be arbitrarly defined by the - 80 g.u. isogal. On both sides of the graben the zones extend furthest into the Midland Valley at the SW limit of the region.

(2) a salient of higher values extends north-westwards from this zone across the Lesmahagow Inlier

towards Distinkhorn;

(3) Beyond these marginal zones, and within the Midland Valley, the average background value is -100 g.u., and more than half of the region studied lies between isogals -80 and -130 g.u.. Variations above or below these values are characteristically associated with steeper gradients, otherwise the gradients are comparatively gentle. An extensive area of this type (background value about -100 g.u. and with low gradients) is present in north and central Ayrshire, to the north of the Inchgotrick Fault

(4) a Low A-B, on the SE (downthrown) side of the Highland Boundary Fault, which trends parallel to the fault. Its lowest (axial) values occur at about 9 km from the fault;

AND EITHER (SET 1, see Fig. 21)

(5) a very large near-circular Low C, centred a few kilometers to the SE of Hamilton; (6) a High D, centred near Bathgate, which is oval with its longer axis trending WNW /ESE; (7) a low E trending E /W (swinging to ENE /WSW) with its axis passing near Clackmannan;

OR (SET 1 a, see Fig. 20)

(8) lows C and E are in continuity forming a NE /SW orientated minimum trough uninterrupted by any of High D.

Most of these features may also be recognised in Residual Set 2 (Fig. 19). The principal differences are

(1) the surface-fitting procedure (p. 78) has oblitrated most of the marginal zones of steep gradient (except around Loch Lomond);

(2) the Lesmahagow (high) salient is slightly more discrete and better defined;

(3) the average background values within the low-gradients area of the graben is, -10 g.u., and low-gradients tend to be associated with values in the range -10 to -20 g.u.;

(4) Low B is more distinct with a definite increase in gravity values on the SE flank towards the axial zone of the graben;

AND EITHER (SET 2)

(5) Low C is still the most prominent feature within the graben, with no loss of amplitude, although its absolute peak value is only half that of Set 1's value;

(6) High D retains the same oval shape, the only significant difference is in the absolute value at the peak of the anomaly;

(7) Low E is more definitely of E /W trend, otherwise the only significant change is in the absolute values of the anomalies.

OR (8) (SET 2 a) in which High D is suppressed and Lows C and E joined together.

4.2 Inversion of the final residual anomalies to density-models

(In this section Residual (with a capital 'R') refers to corrected Bouguer anomalies (of Sets 1 and 2), and residuals (with small "r") refers to differences between observed and calculated model anomalies).

Both Set 1 (the most probable) and Set 2 (the practical lower limit of Lower Old Red Sandstone thicknesses) of final Residual anomalies are interpreted as density-models (Figs. 22 and 24) using a gravity modelling computer program written by Powell (pers. comm.) (Hossain, 1976). In this program the top of the model was fixed at sea-level (O.D. Newlyn). The spacing of the points along the profiles is 5 km in a NW/SE orientation, while the spacing between the profiles is 12.5 km.

The lateral limits of the low density rocks in the model are taken at the Midland Valley boundary faults. A density contrast of -70 kg m^{-3} is used for the model, and corresponds to that between Lower Palaeozoic -Precambrian rocks (2720 kg m^{-3}) and Upper Old Red Sandstone strata (2650 kg m^{-3}). This density contrast (-70 kg m^{-3}) is also close to that which would arise between a granite mass and Lower Palaeozoic country rocks into which it was emplaced.

The anomaly datum for the Set 2 Residuals remains to be defined. At levels much below +70 g.u., positive anomalies would appear within the Midland Valley. At levels above +70 g.u. the 'tails' of the expected negative anomalies extend too far beyond the bounding faults to be modelled by low-density material bounded by them; thus residuals begin to increase in these areas. The end-point base-depths of the iteratively adjusted model also depend upon the starting point. This is due to the way in which the program adjusts, on each iteration. Only those depth points that are under |residuals| which are greater than average). It would be difficult to choose, on the basis of average residuals, between models covering a range of depth variation. That chosen inversion (Fig. 24) has a low average residual (5.4 g.u.) and low depth variation compared with explored alternatives.

The anomaly datum for Set 1 anomalies has been defined at the same time as the regional (loosely defined to make Residuals zero along the Southern Uplands Fault). The positive residuals from calculation show that the regional has truncated the anomaly tails south of the Southern Uplands Fault too abruptly. North of the Highland

Boundary Fault, however, whilst residuals in one area are positive in another they are negative, so that a constant adjustment to the datum could not improve both. The best average residuals found for Set 1 inversions are, at leastly partly on this account, three times as big as those for Set 2. This tends to increase the range of depth variation within a model which gives as good a fit as another. Thus under Low C (or C and E combined as in Set 1 a) the base may be as deep as 25 km rather than 12 km (Fig. 22) i.e. if more deep-going models favour an intrusive interpretation (see Section 4.3.3), descrimination is not possible on the basis of the presently achieved the regional.

4.3 The major gravity anomalies and their geological interpretation (Fig. 19, 20 and 21)

4.3.1 The background or average value of residual anomalies within the graben The background value of the residual anomalies in Set 1, clear of the marginal gradients and of the distinct local anomalies within the graben, is approaximately -100 g.u. with respect to zero values over the marginal, Lower Palaeozoic outcrops. This corresponds to a thickness of Lower Old Red Sandstone /Upper Silurian of _c._ 4 km (Fig. 23).

The thicknesses of Lower Old Red Sandstone /Upper Silurian strata (plus Upper Old Red Sandstone and other strata below base of the Clyde Plateau Lavas) are obtained (Fig. 23) by subtracting the base of Clyde Plateau Lavas depths (Fig. 14) from the values of Fig. 22 (thicknesses around 4 km) are seen to occupy about 40 % of the area analysed, and are mostly confined to the central region of the graben. Whereas thicknesses greater than 4 km, defining 'basins', occur especially towards the Highland Boundary Fault margin.

The thicknesses shown on the density-models represent only preserved thicknesses and not the original thicknesses, thus it is not possible to say from this evidence whether these are original basins of sedimentation or subsequent synclinal basins.

4.3.2 Low A-B

Low A-B has been recognised and discussed by Qureshi (1970, 487) and its probable prolongation to the SW by McLean and Qureshi (1966, 270) and McLean and Walker (1978, 35, 36). It trends parallel to the Highland Boundary Fault between north Renfrewshire and the area SE of Callander. Further north-eastwards, near the margin of the region analysed, it appears to swing into, and across the fault - probably as a result of imperfect reduction of

*

In contrast, the supposition used to get Set 1, that the component towards the SE seen in the Southern Highlands persists into the Midland Valley, is probable in this zone. The resolution of the field and definition of the local (i.e. Old Red Sandstone anomaly) is better along NW/SE profiles. However, the difference in change of gravity along the fault zone between A and B which is determined by the south-westerly crustal component, is probably better represented by the 3rd order surface. The reason is that the magnitude and best average value of this component is arrived at in the third order surface by using all the gravity evidence. The estimate arrived at in the other method (Set 1) uses only the profiles (LISPB and McLean and Qureshi) and ignores the observed gradients in the Southern Highlands. This means that the changes in basin development between A and B may be better represented by Set 2.

data at the edges of the area. To the SW, the axis of the low does not persist as far as the Clyde coast, and the West Kilbride Low (McLean, 1966, 257-259) (A' on Fig. 21) may represent a similar, en echelon structure.

The change of gravity from the Highlands to the axis of Low B (that is across the NW flank of Low B) differs slightly between Residual Set 1 and Set 2. As discussed earlier (p. 85) the fitting process used in getting the crustal component for Set 2 smears the gravity changes across the Highland Boundary Fault for a distance of several kilometres on both sides of it. The Set 2 Residuals near the fault are therefore less usefull for interpretation as a density-model (although more treatable to numerical modelling).*

In this zone there is also good geological control on the relative contributions of Upper and Lower Old Red Sandstone, since Low A crosses the Lower Old Red Sandstone outcrop for almost half its course and the density-model (Fig. 23) shows a preserved thickness of 2 km west of Loch Lomond to 4 km of Old Red

Sandstone 8 km east of Loch Lomond. In the wedge immediately west of Loch Lomond the preserved thickness of both Upper and Lower Old Red Sandstone is 2 km, and since the geological estimate of the Upper Old Red Sandstone thickness (near Helensburgh) is *c.* 0.6 km then the preserved thickness of the Lower Old Red Sandstone is 1.1 km. In the area where the Upper Old Red Sandstone outcrops to the South-east of Loch Lomond, the estimated geological thicknesses vary between *c.* 0.8 km near Killearn on the north side of the Kilpatrick Hills and the Campsies to 0.4 km further west (MacGregor and MacGregor, 1948, 30). When compared with the calculated 4.2 km and 4.8 km thickness of Old Red Sandstone these will become 3 km and 4.2 km respectively of Lower Old Red Sandstone preserved in these areas.

4.3.3 Low C / E

Low C is recognisable in the original Bouguer anomalies map (Fig. 5) and at all stages of reduction by stripping. In the final maps (Figs. 19 and 21) it is the largest local anomaly within the area of the graben.

The density-model based on Set 1 Residuals (Figs. 20, 21)) shows basement at a depth of 12 km, and a maximum thickness of 11 km (Fig. 23) of rock of density 2650 kg m^{-3} at its centre. This magnitude, which could be even greater than 12 km, favours the interpretation that the low-density rock is within the Crystalline basement, as a granite, and not more than, say 1/3 of the thickness attributable as Upper Silurian /Lower Old Red Sandstone strata. The near-circular form of the anomaly (Set 1) would be consistent with a stock-like mass. A simple cylindrical model is computed (Fig. 26) to test this possibility and to indicate the approximate size of the granite body. Similarly, on Fig. 20, (Set 1 a) the anomaly amplitude still favours the interpretation that the low-density rock is granite but now one which is elongated in plan. A more exhaustive analysis seems unjustified with the data available.

Any granite body which produces most of Low C or Low C-E would have a diameter of c. 22 km. In comparison, some of the larger granites from the Southern Uplands and the Highlands show similar diameters. This would be a maximal size since part of the anomaly may be related to an Upper Silurian /Lower Old Red Sandstone basin.

Apart from the exposed Lower Old Red Sandstone granitic intrusion at Distinkhorn, lying just SW of the concealed granite intrusion postulated here, the Ordovician exposure of older granites under the Midland Valley has been proposed by Longman et al. (1979).

The average lower limit of magnitude is derived from Residual Set 2 (Fig. 19). It gives a maximum thickness of 8 km (Fig. 25). Even this is rather great to be explicable readily as a basin (Set 2) or an elongated trough (Set 2 a) infilled with Upper Silurian /Lower Old Red Sandstone strata (but see 4.4).

There is no geological basis for reducing this figure by postulating that part of the gravity effect is due to Upper Old Red Sandstone, with a greater density contrast, because that formation is overstepped by the Carboniferous in the whole of the area of its potential outcrop around the southern side of the 'basin'.

There is, however, some evidence from a few samples that the density of the Downtonian (2540 kg m^{-3}) is as much as 100 kg m^{-3} less than the average density for Downtonian and Lower Old Red Sandstone. If such rocks characterise a significant part of the infilling to a basin under Lows C/E then the 8 km thickness could be an overestimate.

One suggestive correlation seen on all maps (Figs. 19, 20 and 21) is that the Inchgotrick Fault swings in a smooth curve as it approached Low C/E, and terminates at its centre. The pattern is similar to a crack in plate 'keying-in' to a pre-existing circular hole. It is seen at the Tertiary Igneous Centres of western Scotland, where dyke- swarms key-in to the ring-intrusions. It suggests that the easterly development of the Inchgotrick Fault is controled by the inferred granite pluton. If this argument is valid, it is implicit that the pluton is pre-Inchgotrick Fault in age i.e. pre-Lower Carboniferous.

4.3.4 High D

The magnetic high which is closely associated with High D has been studied by Powell (1971) and Gunn (1975), and both presented a probable model and geological interpretation of the magnetic source. More recently Hossain (1976) revised their interpretation by making a combined study of both the magnetic and gravity anomalies. The critical step of separating out a local, Bathgate, Bouguer anomaly from the total field involved a pseudo-gravity calculation of the magnetic body.

In the present study the pseudo-gravity effects of a similar magnetic body were stripped from the total field in the process of obtaining the final Residual maps (Figs. 17, 18, 19). It is reasonable to suppose that around Bathgate the magnetic effect of the intrusion far exceeds that of any of Clyde Plateau Lavas since the latter are thin (less than 0.5 km) under the area immediately to the west.

Two posibilities were considered in calculating the pseudo-gravity effect of this intrusion :

(1) the density of the intrusion equals that of the Clyde Plateau Lavas (Lower Old Red Sandstone replacement density

contrast of - 70 kg m^{-3}), not requiring separate definition of the intrusion. The pseudo-gravity correction associated with this model leaves a Residual gravity High (D) on the site of the observed High separating Residual Lows C and E.

(2) The density of intrusion is 2850 kg m^{-3} appropriate to gabbro (Lower Old Red Sandstone replacement density contrast - 200 kg m^{-3}) and is applied to all magnetic model thicknesses East of [270] on the assumption that the Clyde plateau Lavas contribution is negligible. This correction virtually compensates for the observed gravity high. On the Residual map (Fig. 20) Lows C and E now tend to form a continuous feature.

An interpretation with possibility (1) produced from Set 2 Residuals (Figs. 19,25) suggests that no Lower Old Red Sandstone /Upper Silurian strata exist beneath the intrusion i.e. the Residual amplitude is equal to the pseudo-gravity of Lower Old Red Sandstone replacement effect of the intrusion around High D. This result shows that the 70 g.u. reference level for this set of anomalies is consistent with the assumed basement density (2720 kg m^{-3}).

The alternative interpretation (Fig. 20) suggests, consequentially, that the depth extent of the intrusive basic mass associated with Clyde Plateau Lavas is only a half of the thickness of the low-density rocks which surround and underlie it (see 4.3.3).

4.4 General discussion

The density-models presented for the Lower Old Red Sandstone in the Midland Valley of Scotland (Fig. 25, 23) represent only the preserved thicknesses of the Lower Old Red Sandstone / Upper Silurian and not the original thicknesses. Although the absolute values of these preserved thicknesses are dependent on the poorly controlled choice of the crustal component, the general pattern of thickness variation is more certain.

There is a clear relationship between the Highland Boundary Fault and the Strathmore basin plus its south-western extension where Old Red Sandstone thicknesses of upto 9 km are interpreted. This is consistent with Bluck's model (1978, Fig. 4(b)) in which subsidence is associated with the development of the Highland Boundary Fault in Lower Old Red Sandstone times. In contrast, and in the southern part of the map, close to the Southern Uplands Fault, there is only a gradual north-easterly thickening of the strata and no local trough associated with the Fault (cf. Bluck, 1978, Fig.

20). If Bluck's "Lanark basin" exists it would have to lie north of the Inchgotrick Fault; (Low C possibly extending to Low E). Both these alternatives i.e. no Lanark basin or its axial position represent a considerable modification to Bluck's model.

CHAPTER FIVE

GEOLOGICAL CONCLUSIONS

5.1 From magnetic anomalies

1. The maximum or thickest (1.25 km) development of the Clyde Plateau Lavas is along a NW / SE axis, extending from the Renfrewshire Hills to the Strathaven Hills. These Lavas thin to less than 0.5 km under the Hamilton Coalfield basin to the east. North of the Clyde the Lavas are relatively thin (0.5 km).

2. The Dusk Water Fault appears to be the most important fracture in terms of movement contemporaneous with the eruption of the Clyde Plateau Lavas. The Lavas are thicker to the south (1.25 km) than to the north (0.75 km) of it.

3. Two magnetic anomalies are interpreted as due to intrusions associated with Lavas (Waterhead and Bathgate), since their 'equivalent thicknesses' are considered to be too great (1.5; 3.0 km respectively) for Lavas in their respective areas.

5.2 From gravity Residuals (corrected for known and magnetically inferred geology) and Residuals (and / or) crustal gravity components

1. The average thickness of Old Red Sandstone within the western graben of the Midland Valley is at least 2.5 may be as much as 4 km as (particularly in the central part).

2. The existence of thick (up to 9 km) Lower Old Red Sandstone within a basin adjacent and parallel to the Highland Boundary Fault is confirmed. The thickness in the basin tends to diminish towards the SW.

3. There is not, however, an apparent symmetrical development of basins on the south eastern margin of the Midland valley graben. In the south adjacent to the Southern Uplands Fault, the strata thicken steadily into the graben in a direction not quite normal to the Fault, until average values of thickness are present.

4. In the wide central zone of the Midland Valley there is a very large, near-circular gravity low, centred a few kilometers to the south east of Hamilton. Two alternative explanations of the anomalies are proposed:

Either (a) that there is no local basinal development of Old Red Sandstone , and the gravity Low C is due to a granitic batholith intruded into the crystalline basement and possibly the Old Red Sandstone. Its diameter of c. 22 km is similar to that of some Newer granites in the Highlands and the Southern Uplands. If this body exists , then NE termination of the Inchgotrick Fault has been controlled by it; or (b) there is a NE / SW trending Old Red Sandstone basin (Lows C and E), comparable in dimensions with the largest adjacent to the Highland Boundary Fault. Its axis would lie north of the projection of the Inchgotrick Fault.

REFERENCES

Al-Salman, S.H.A. (1974)

Study of the gravity anomalies in the central parts of Southern Uplands of Scotland. University of London PHD thesis [Unpublished].

Anderson, E.M. (1951)

The Dynamics of Faulting (2nd ed.). (Edinburgh: Oliver and Boyd).

Bacon, M. (1972)

Network Reduction System, Marine Geophysics Unit, Computer Rep. 15,. [Unpublished].

Bamford, D.; Nunn, K. Prodehl, C. and Jac ob, B. (1976)

A lithospheric seismic profile in Britain. Geophys. J. R. astr. Soc. 44, 145-160.

Bamford, D.; Nunn, K. Prodehl, C. and Jac ob, B. (1977)

LISPB-III. Upper crustal structure of northern Britain. Jl. geol. Soc. Lond. 133, 481-488

Bluck, B.J. (1978 a)

Geology of a continental margin 1: the Ballantrae Complex. In (Bowes, D.R. and Leake, B.E. (ed.)). Crustal evolution in northwestern Britain and adjacent regions. 151-162, geol. J. Spec. Issue., No. 10.

Bluck, B.J. (1978)

Sedimentation in a late orogenic basin: the Old Red Sandstone of the Midland Valley of Scotland. In (Bowes, D.R. and Leake, B.E. (ed.)). Crustal evolution in northwestern Britain and adjacent regions. 249-278, Geol. J. Spec. Issue., No. 10.

Bott, M.H.P. and Masson-Smith, D. (1960)

A gravity survey of the Cairnsmore of Fleet granite and its environs. Scott. J. Geol. 9, 219-231.

Bullerwell, W. (1968)

Aeromagnetic Map of Great Britain (sheet 11).

Cotton, W.R. (1968)

A geological survey of the Campsies and Kilpatriuck Hills. University of Glasgow PHD thesis [Unpublished].

Dewey, J.F. (1971)

A model for the Lower Palaeozoic evolution of the southern margin of the Early Caledonides of Scotland and Ireland. Scott. J. Geol. 7, 219-240

El-Batroukh, S.I. (1975)

Geophysical investigations of Loch doon Granite in south west Scotland. University of Glasgow PHD thesis [Unpublished].

Eyles, V.A., Simpson, J.B. and MacGregor, A.G. (1949)

The geology of central Ayrshire. Mem. geol. Surv. U.K.

George, T.N. (1958)

Lower Carboniferous Paleogeography of the British Isles. Proc. Yorks. geol. Soc. 31, 227-317.

George, T.N. (1960)

The stratigraphical evolution of the Midland Valley. Trans. geol. Soc. Glasgow. 24, 32-107.

Goodlet, G.A. (1957)

Lithological variations in the Lower Limestone Groups in the Midland Valley of Scotland. Bull. geol. Surv. U.K. 12, 52-65.

Graham, A.M. and Upton, B.G.J. (1978)

Gneisses in diatrems, scottish Midland valley petrology and tectonic implications. Jl. geol. Soc. Lond. 135, 219-229.

Gunn, P. J. (1975)

Interpretation of the Bathgate magnetic anomaly, Midland Valley, Scotland. Scott. J. Geol. 3, 263-266.

Gunn, P.J. (1973)

Location of the proto-Atlantic suture in the British Isles. Nature Lond. 242, 111-112.

Hall, J. (1971)

A preliminary seismic survey adjacent to the

Rashiehill borehole near Salamanan, Stirlingshire. Scott. J. Geol. 7, 170-174.

Hall, J. (1974)
A seismic reflection survey of the Clyde Plateau Lavas in north Ayrshire and renfrewshire. Scott. J. Geol. 9, 252-279.

Hess, H.H. (1955)
Serpentines, orogeny and epeirogeny. geol. Soc. Amer. Spec. Paper, 62, 391-407.

Hossain, M.M.A. (1976) Anylysis of the major gravity and magnetic anomalies centred about Bathgate, Central Scotland. University of Glasgow MSc thesis [Unpublished].

Kennedy, W.Q. (1958)
The tectonic evolution of the Midland Valley of Scotland. Trans. geol. Soc. Glasgow. 23, 107-133.

Lagios, E and Hipkin, R.G. (1979)
The Tweeddale granite- a newly discovered batholith in the Southern Uplands. Nature Lond. 280, 672-675.

Longman, C.D.; Bluck, B.J. and Breeman, O'Van. (1979)
Ordovician conglomerates and the evolution of the Midland Valley. Nature Lond. 208, 578-581.

MacGregor, M. and MacGregor, A.G. (1948)
British regional geology: The Midland valley of

Scotland. Mem. geol. Surv. U.K.

Mansfield, J. and Kennett, P. (1963)
A gravity survey of the Stranraer sedimentary basin. Proc. Yorks. geol. Soc. 34, 139-151

Masson-Smith, D.; Howel, P.M. and Abernethy-Clark, A.B.D.E. (1974)
The National Gravity Reference Net 1963 (NGRN 73). Ordnance Survey Professional Papers No. 26.

McKerrow, W.S.; Legget, J.K. and Eales, M.H. (1977)
Imbricate Thrust model of the Southern Uplands of Scotland. Nature Lond. 267, 237-239.

McLean, A.C. (1961a)
A gravity survey of the Sanquhar Coalfield. Proc. R. Soc. Edinburgh. 66, 112-127.

McLean, A.C. (1961b)
Density measurements of rocks in south-west Scotland. Proc. R. Soc. Edinburgh. 68, 103-111.

McLean, A.C. (1966)
A gravity survey in Ayrshire and its geological interpretation. Trans. R. Soc. Edinburgh. 68, 239-283.

McLean, A.C. and Deegan, C.E. (1978)
The solid geology of the Clyde sheet (55 N/6 W). IGS Rep. 78/9.

McLean, A.C. and Qureshi, I.R. (1966)

Regional gravity anomalies in the western Midland Valley of Scotland. Trans. R. Soc. Edinburgh. 56, 267-283.

McLean, A.C. and Walker, (1978)

In (McLean, A.C. And Deegan. C.E. (ed.)). The solid geology of the Clyde sheet (55 N/ 6 W). IGS Rep. 78/9.

McLean, A.C. and Wren, A.E. (1978)

In (McLean, A.C. and Deegan, C.E. (ed.)). The solid geology of the Clyde sheet (55 N/ 6 W). IGS Rep. 78/9.

Neeugebauer, H.J. (1978)

Crustal doming and the mechanism of rifting. Part I: rift formation. Tectonophysics. 45, 159-186.

Neugebauer, H.J. and Braner, B. (1978)

Crustal doming and the mechanism of rifting. Part II: rift development of the Upper Rhein graben. Tectonophysics, 46, 1-20.

Park, R.G. (1961)

A vertical force magnetic survey over part of the Dusk Water Fault of north Ayrshire. Trans. geol. Soc. Glasgow. 24, 154-168.

Parslow, G.R. and Randall, B.A. (1973)

A gravity survey of the Cairnsmore of Fleet granite and its environs. Scott. J. Geol. 9, 219-

231.

Philips, W.E.A.; Stillman, C.J. and Murphy, T. (1976)

A Caledonian Plate Tectonic Model. Jl. geol. Soc. Lond. 114, 1-24.

Powell, D.W. (1970)

Magnetised rocks within the Lewisian of western Scotland and Under the Southern Uplands. Scott. J. Geol. 6, 297-301.

Powell, D.W. (1971)

A model for the Upper Palaeozoic evolution of the southern margin of the early Caledonides of Scotland and Ireland. Scott. J. Geol. 7, 369.

Powell, D.W. (1978 a)

Gravity and magnetic anomalies attributable to basement sources under northern Britain. In (Bowes, D.R. and Leake, B.E. (ed.)). Crustal evolution in northwestern Britain and adjacent regions. 107-114. geol. Jl. Spec. Issue. No 10.

Powell, D.W. (1978)

Geology of a continental margin 3: gravity and magnetic anomaly interpretation of the Girvan-Ballantrae district. In (Bowes, D.R. and Leake, B.E. (ed.)). Crustal evolution in northwestern Britain and adjacent regions. 177-182. geol. Jl. Spec. Issue. No. 10.

Qureshi, I.R. (1961)

A gravity survey of the region of the Highland Boundary Fault between Callander and Cowal. University of Glasgow PHD thesis [Unpublished].

Qureshi, I.R. (1970)

A gravity survey of a region of the Highland Boundary Fault in Scotland. Q. Jl. geol. Soc. Lond. 125, 481-502.

Richey, J.E.; Anderson, E.M. and MacGregor, A.G. (1930)

The geology of north Ayrshire. Mem. geol. Surv. U.K.

Smith, P.J. and Bott. M.H.P. (1975)

Structure of the crust beneath the Caledonian Foreland and Caledonian Belt of the North Scottish Shelf Region. Geophys. J. R. astr. Soc. 40, 187-205.

Tuson, J. (1959)

A geological investigation of the Tertiary volcanic districts of western Scotland. University of Durham PHD thesis [Unpublished].

Walker, J.H.D. (1969)

Geophysical and geological measurements in the upper Firth of Clyde. University of Glasgow PHD thesis [Unpublished].

Williams, A. (1962)

The Barr and Lower Ardmillan Series (Caradoc) of the Girvan district, soth east Ayrshire. Mem. geol. Soc. Lond. (3)

Bullerwell. W. (1952)

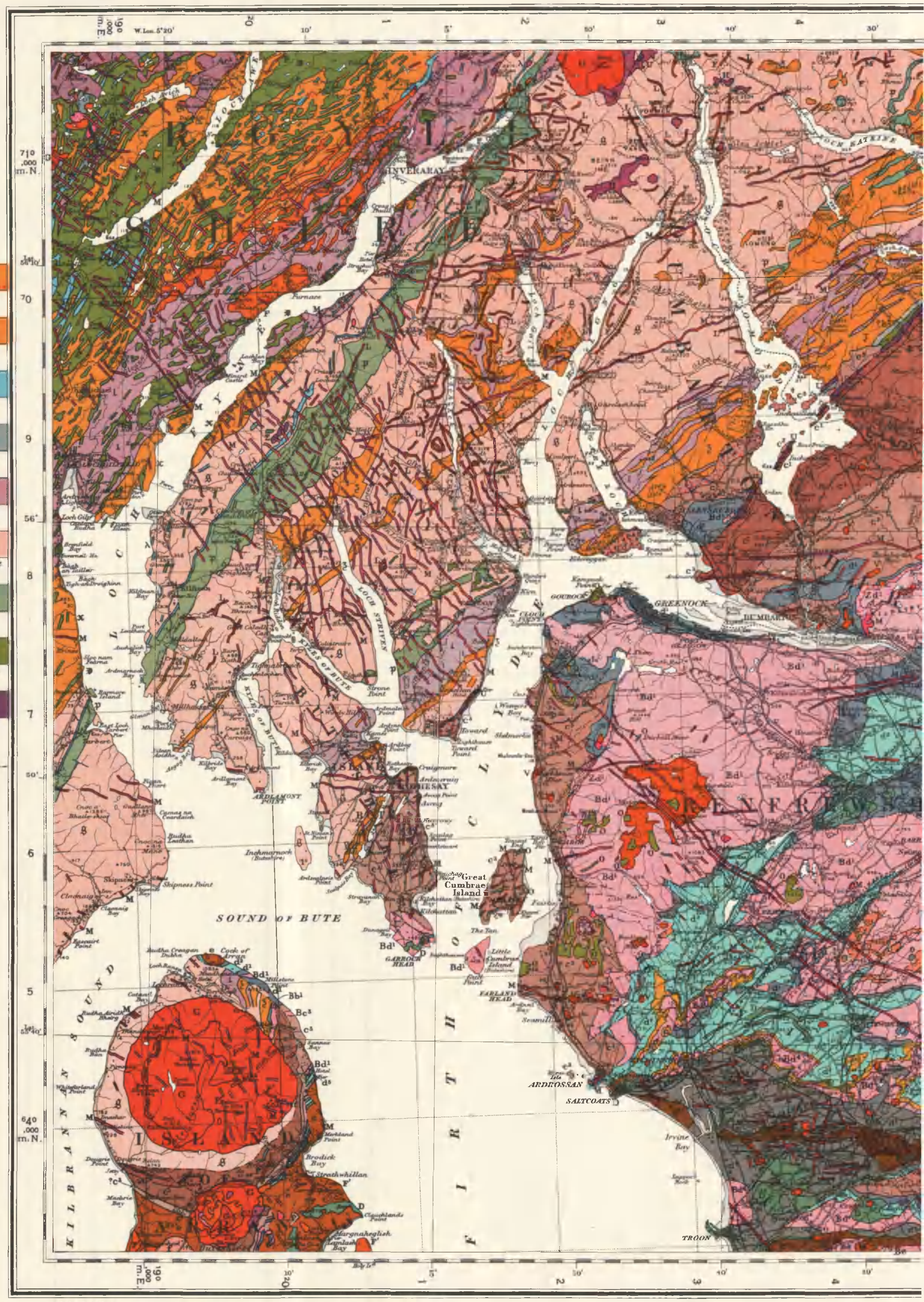
Gravimetric observations comparing Pendulum stations at Cambridge, York, Newcastle Upon Tyne, Edinburgh and Aberdeen. Monthly Notices of the Royal Astronomical Society, Geophysical Supplement, 5, 303-315.

Simpson. J.B. and MacGregor. M.C. (1932)

The economic geology of the Ayrshire Coalfields. Area 4.

ORDNANCE SURVEY OF GREAT BRITAIN

GEOLOGICAL SURVEY OF GREAT BR



EXPLANATION (continued)

METAMORPHOSED SEDIMENTS

- x — Conglomerate; Quartzite, quartz-schist, etc.
- 3 — Schistose grit and greywacke
- λ — Limestone
- $\mathfrak{g}$ — Graphite-schist
- l — Slate, phyllite, etc.
- $\mathfrak{s}$ — Mica-schist, undifferentiated schist
- P — "Green Beds"; Epidotic and chloritic schists and schistose grits

METAMORPHOSED IGNEOUS ROCKS

- Epidiorite, hornblende-schist, etc.
- Serpentine

Faults. A crossmark where shown indicates the downthrow side.

Roads, First Class (Altitude 811)
" Second Class
" Third Class
Railways (Station)
County Boundaries
Church
Site of Battle ×1645

Diagram showing the Numbers of the adjoining Sheets

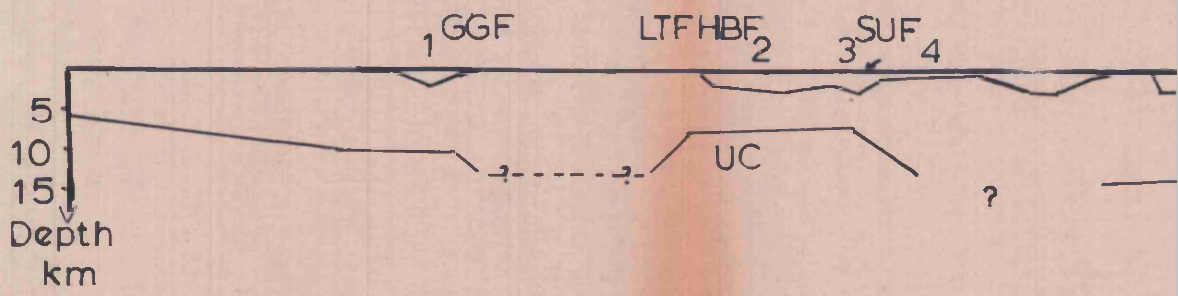
10	11	12
13	14	15
	16	17

Scale of Four Miles to One Inch

Reduced from the One Inch Maps of the Geological Survey.
Published 1931. Sir John S. Flett, K.B.E., *Director.*
Reprinted 1948. W. F. P. McLintock, D.Sc., *Director, Geological Survey. Reprinted (4th impression) 1970.*
1200/70

The Altitudes are given in Feet above the assumed Mean Level of the Sea at Liverpool, which is 0·650 of a Foot

The Altitudes of the Island of Arran are given in Feet above the assumed Mean Lev



VERTICAL EXAGGERATION 4 : 1

Fig. 2

Cross section of the major (crustal) structure
(LISPB, 1977)

GGF Great Glen Fault LTF Loch Tay Fault

HBF Highland Boundary Fault SUF Southern Uplands Fa

UC Upper Crust

1 Cromarty and Moray (Old Red Sandstone)

2 Midland Valley (Old Red Sandstone/Lower Carboni

3 Midlothian Coalfild (Upper and Lower Carbonifero

4 Southern Uplands

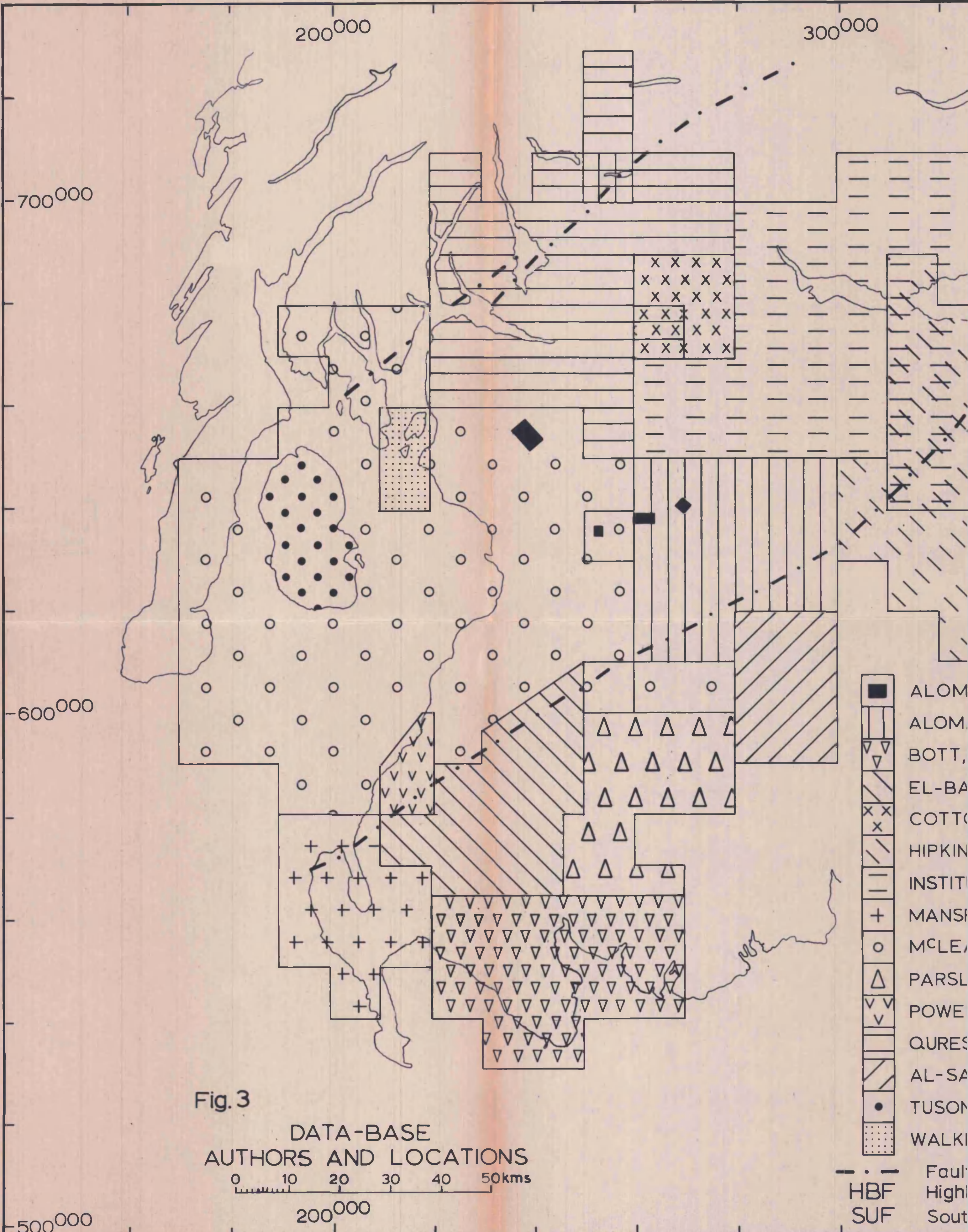
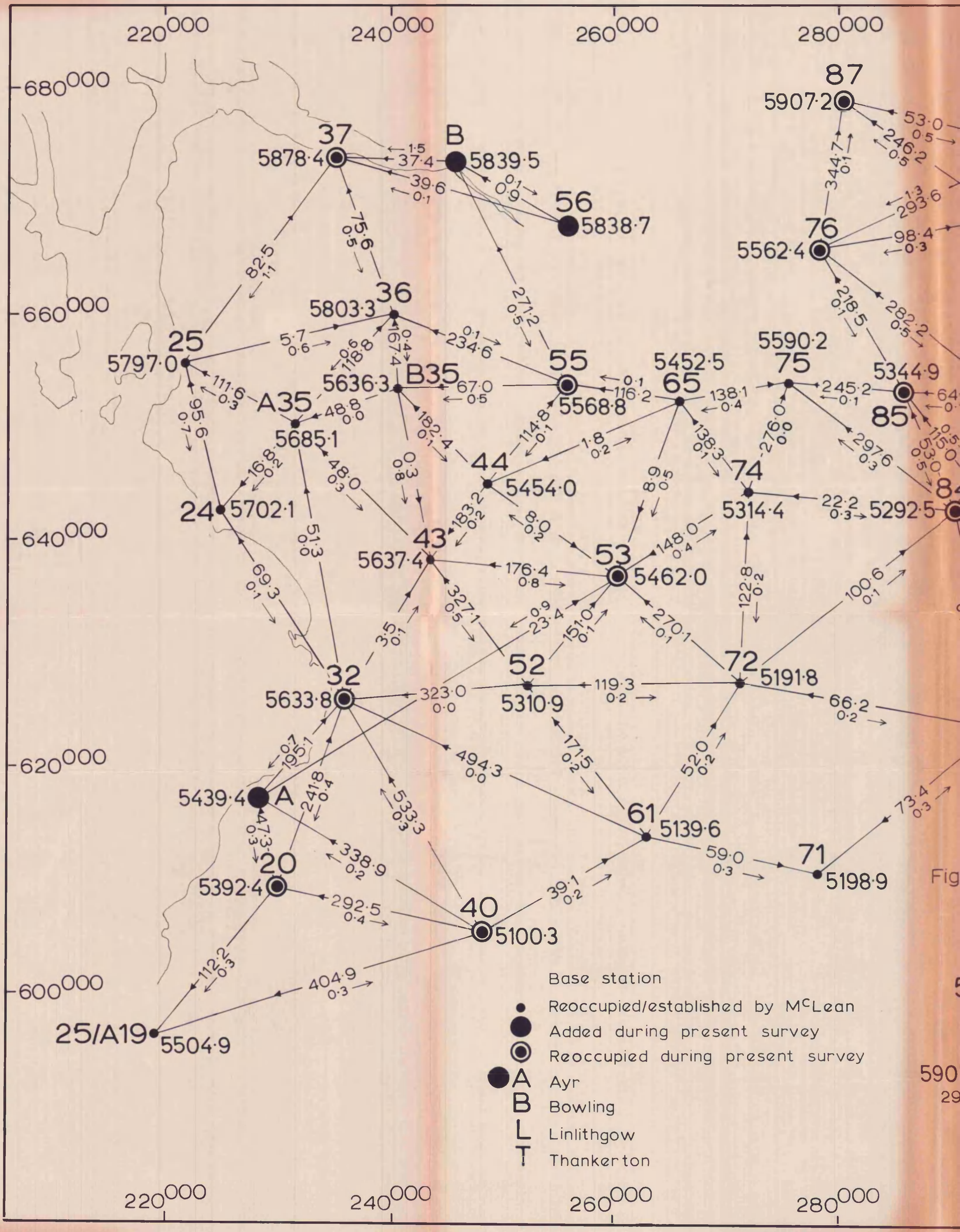


Fig. 3

DATA-BASE
AUTHORS AND LOCATIONS



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Base station
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Added during present survey
Reoccupied during present survey
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L Linlithgow
T Thankerton
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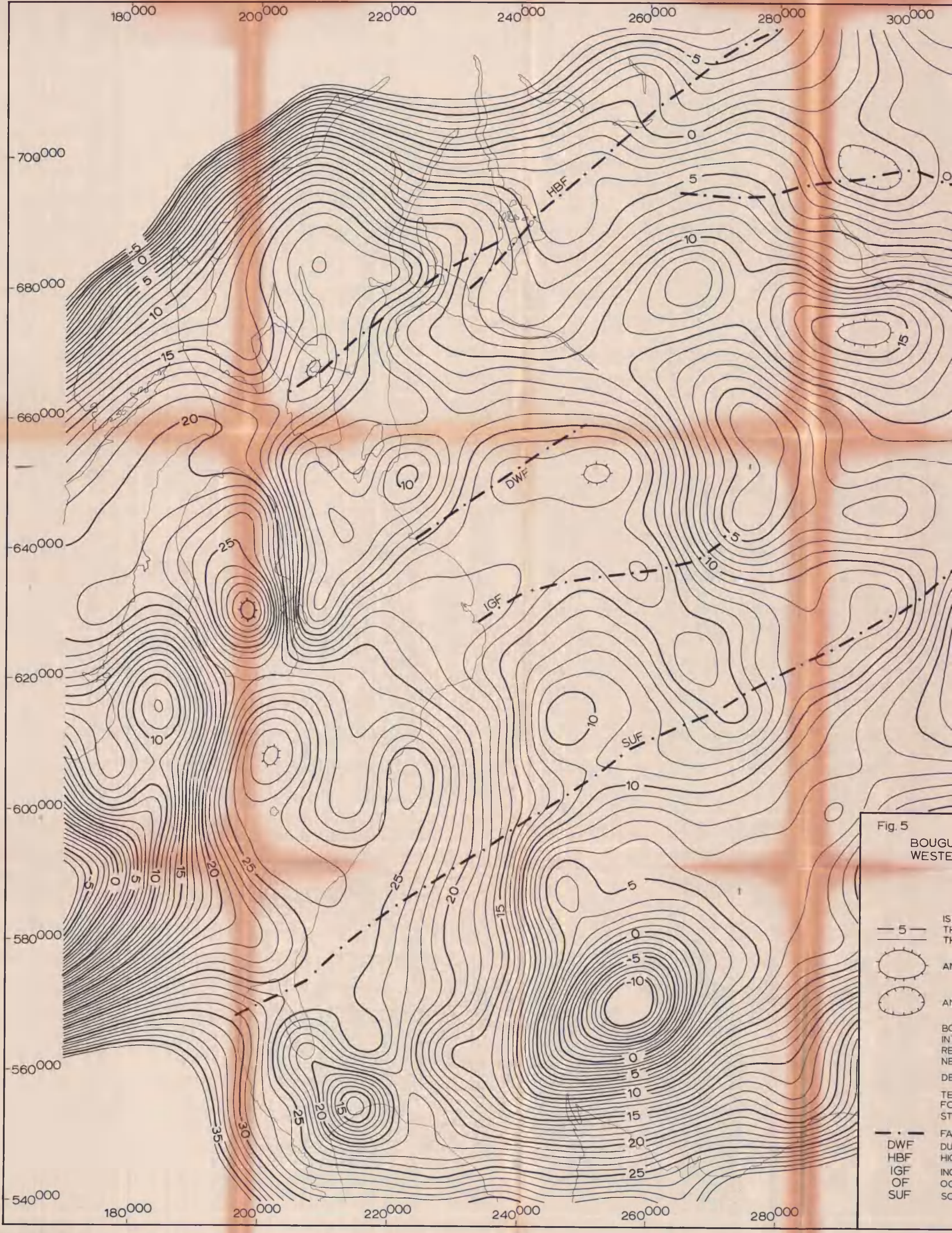

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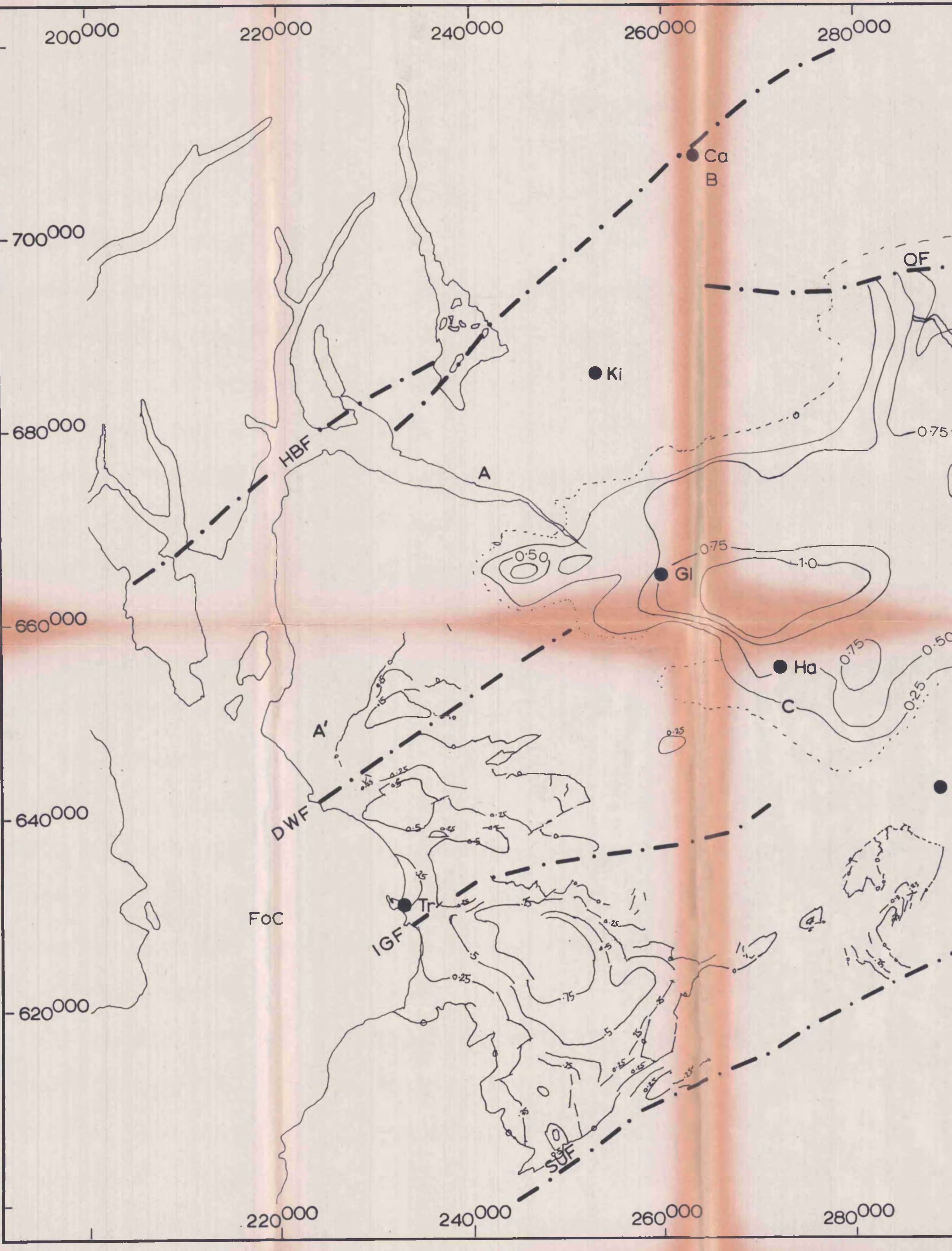
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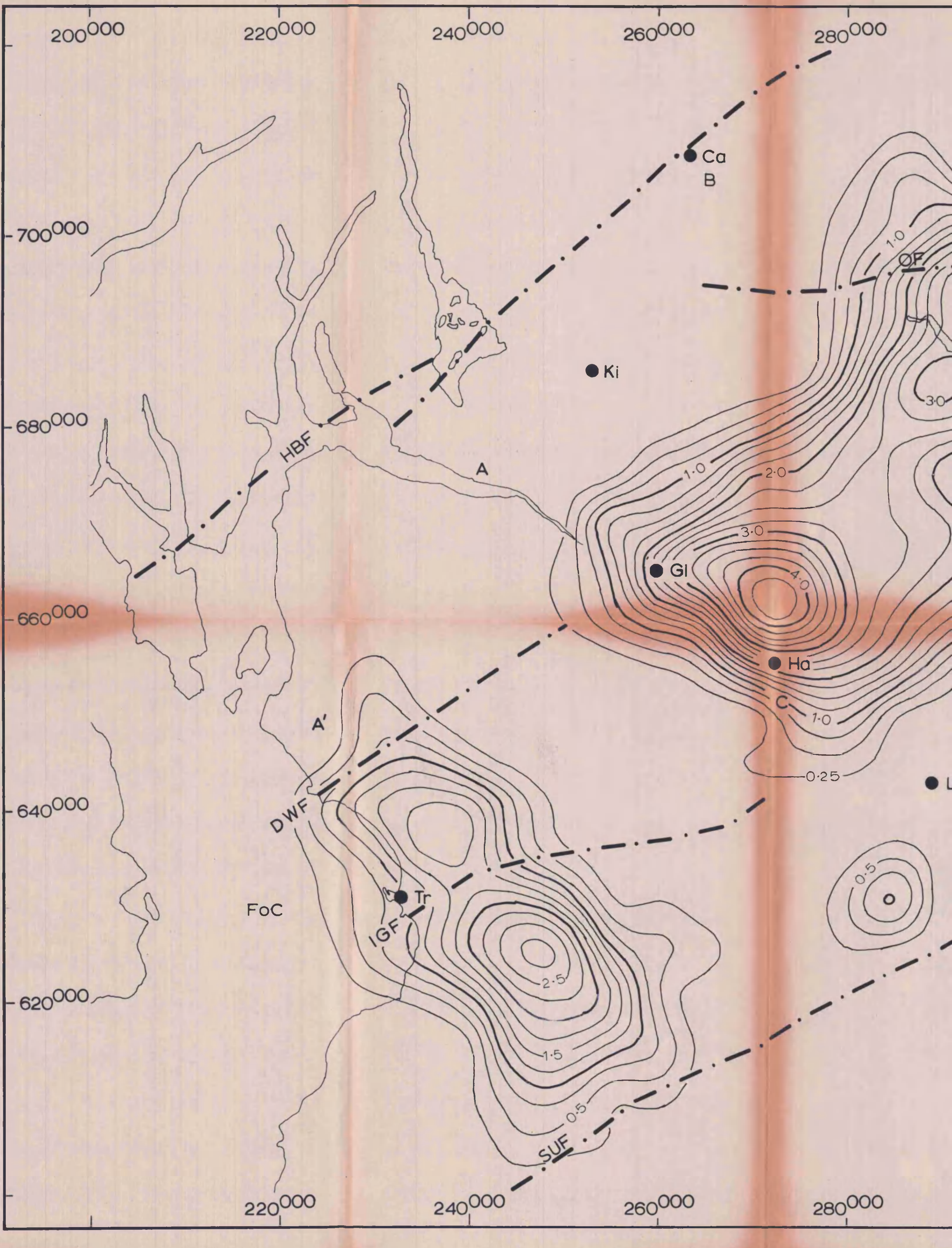

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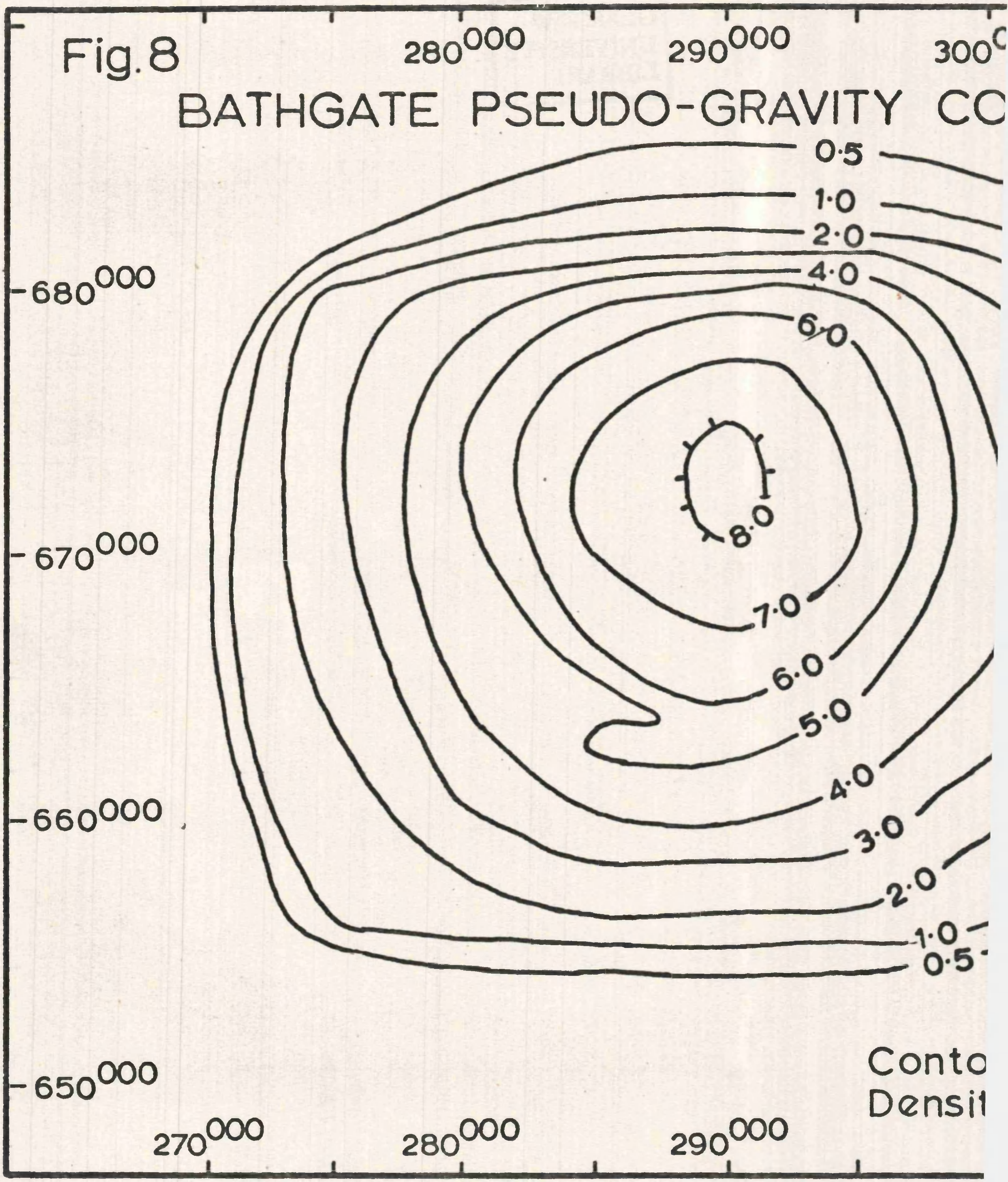
Fig. 8

BATHGATE PSEUDO-GRAVITY CO

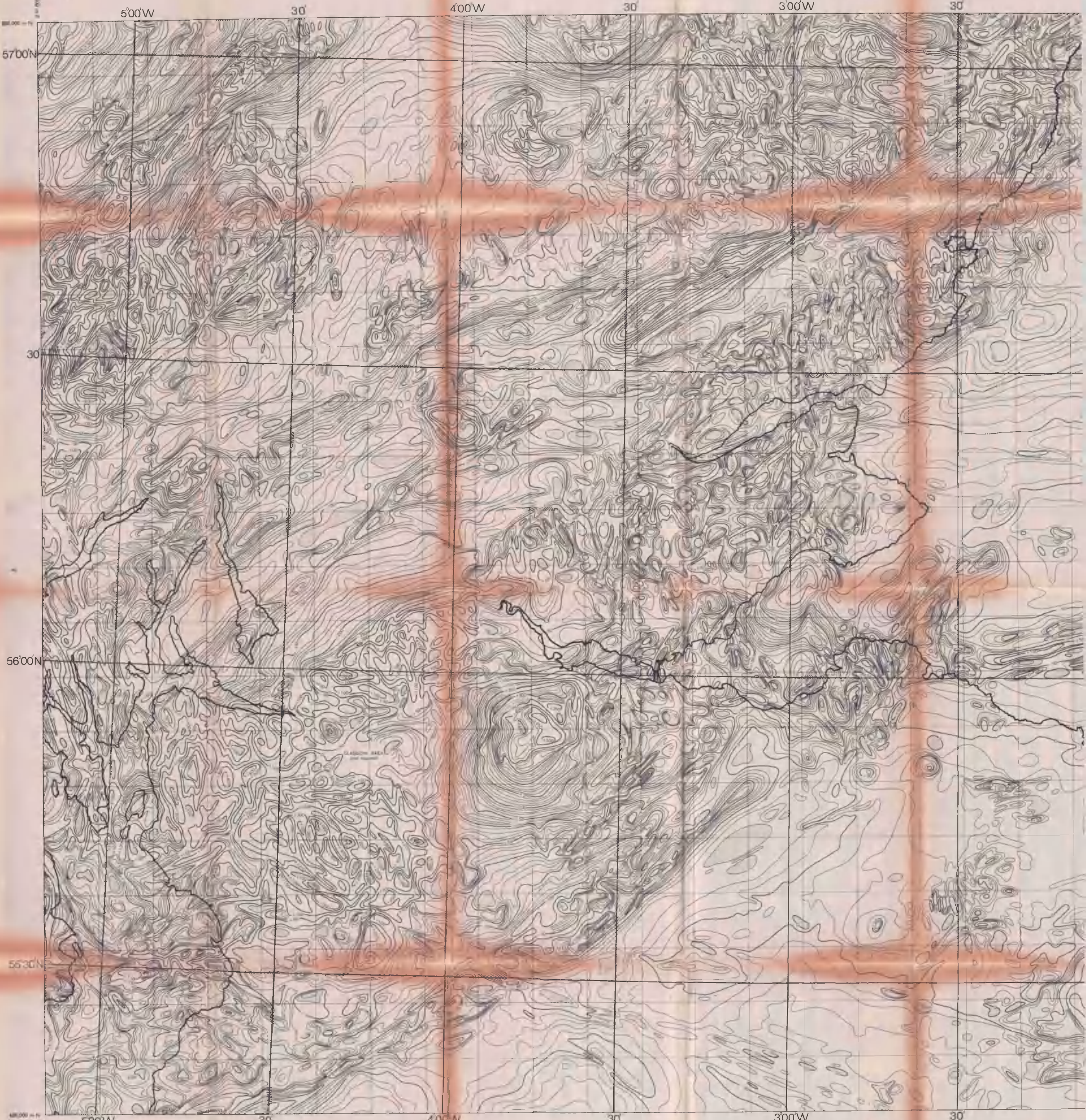


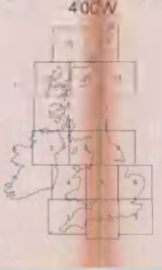
PART OF GREAT BRITAIN & NORTHERN IRELAND

GEOLOGICAL SURVEY
OF
GREAT BRITAIN

NATIONAL GRID
DIAGRAM EDITION

Scale 1:250,000





This sheet covers part of the large area flown between 1959 and 1963 under contract by Canadian Aero Service, Ltd., or by Hunting Surveys, Ltd.

Compiled in Geophysics Department, Geological Survey of Great Britain
W. Bullerwell, Chief Geophysicist. Published 1968
K. C. Dunham, D.Sc., F.R.S., Director, Institute of Geological Sciences incorporating the Geological Survey of Great Britain, the Museum of Practical Geology and Overseas Geological Surveys

gammas. Larger interval in some complex areas, as indicated.

Flight traverse separation 2 km. or closer, with tie lines 10 km or closer. Mean terrain clearance approximates to 1000 feet.

Stippled areas indicate central regions of local magnetic "lows". Unstippled closures denote local "highs".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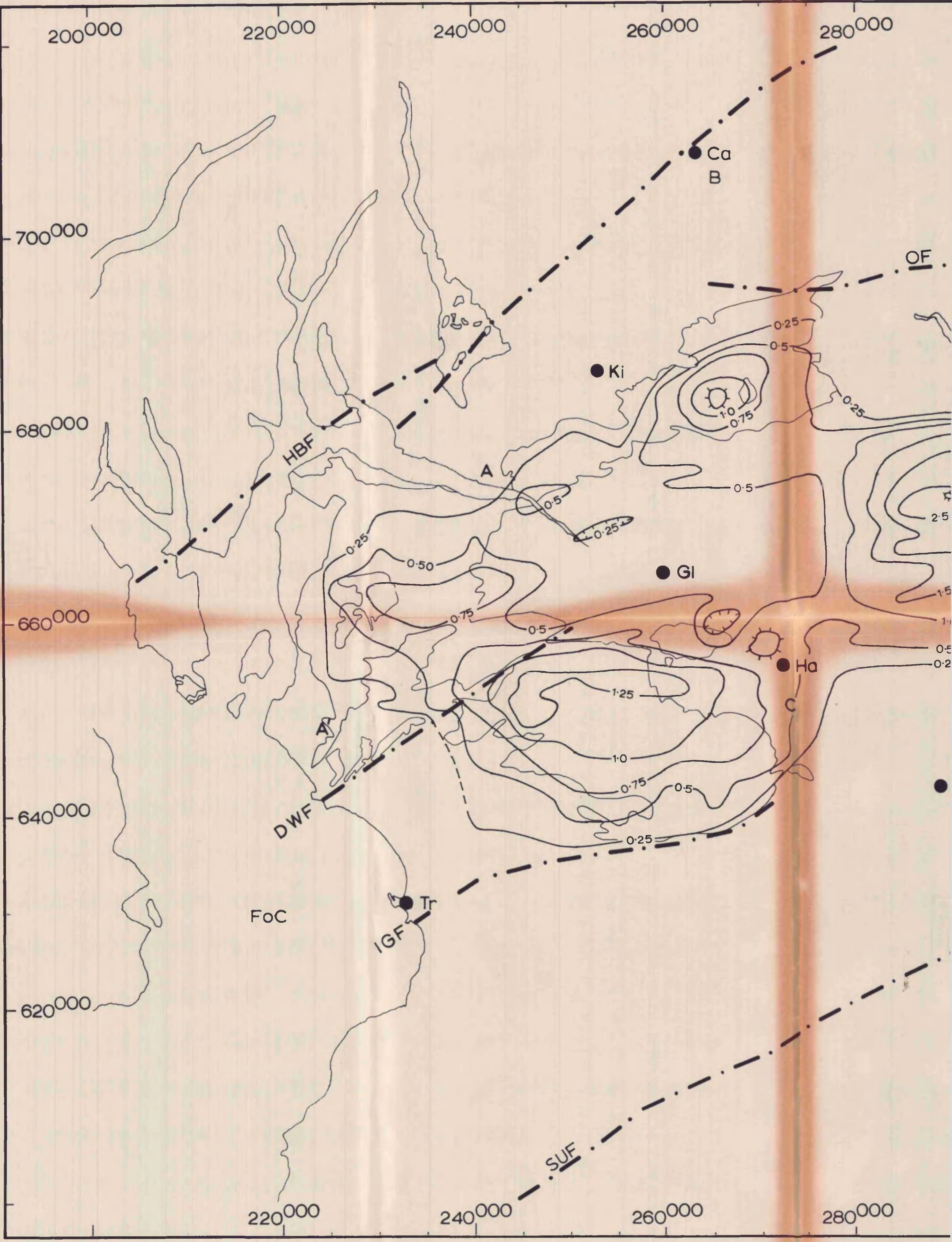

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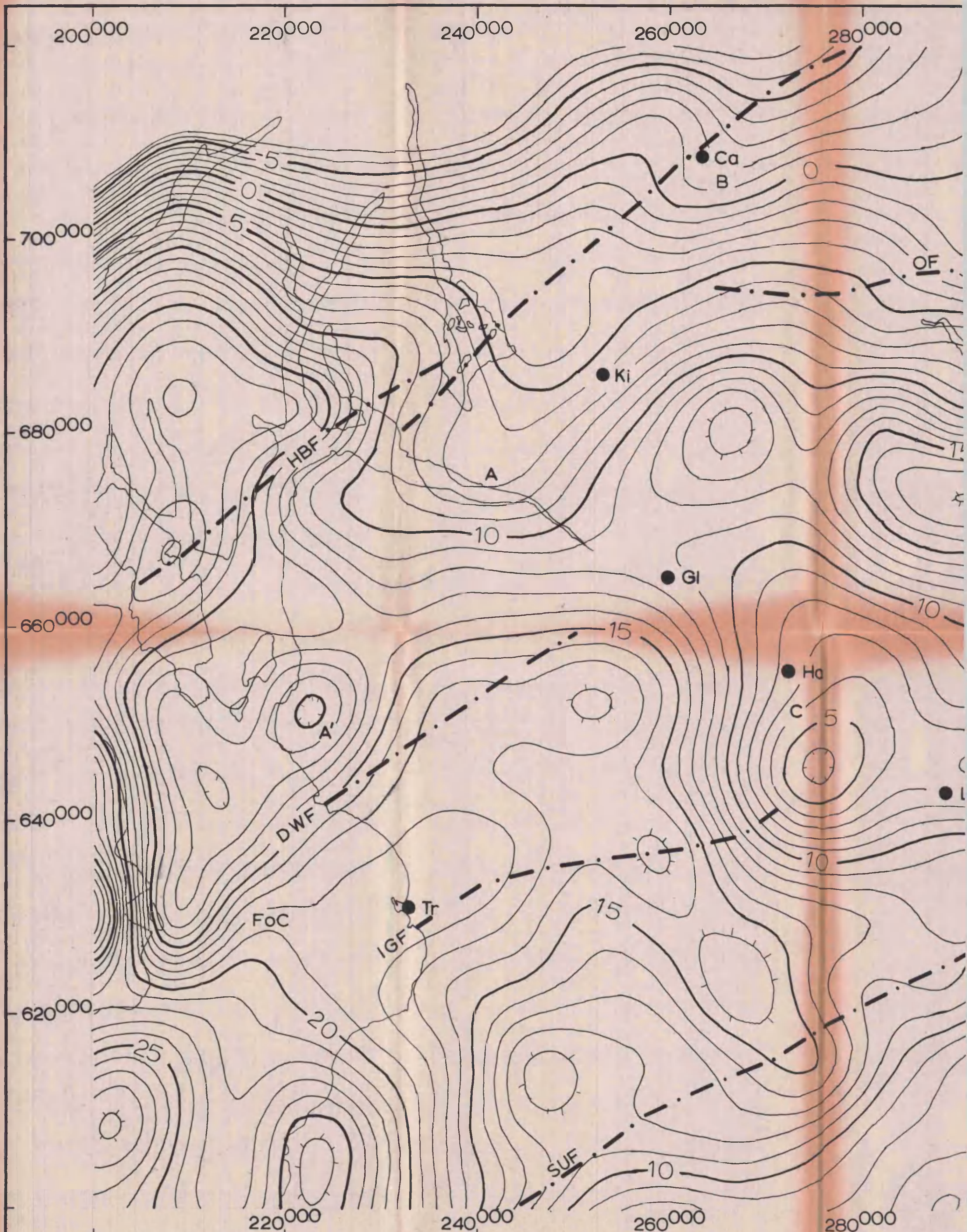

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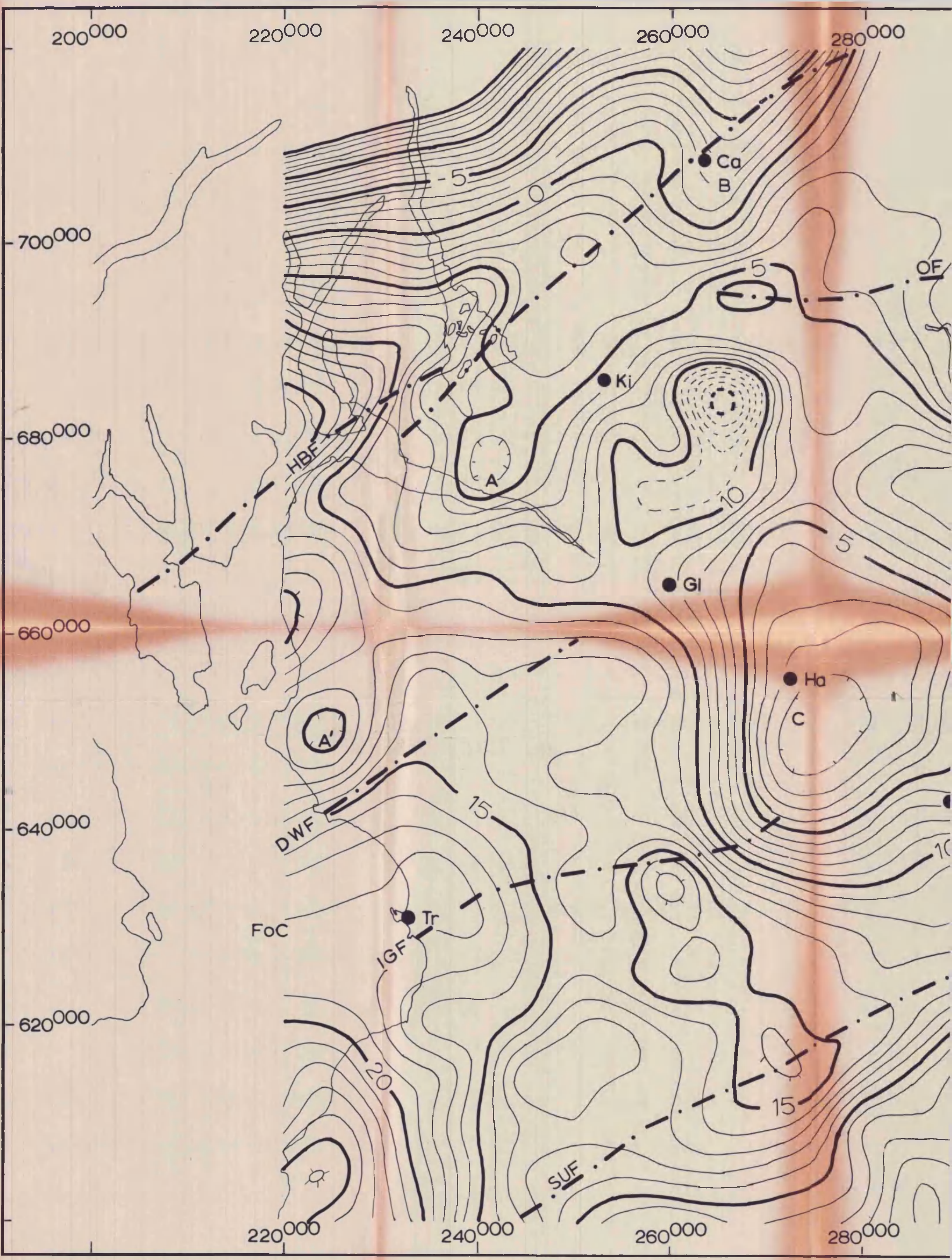

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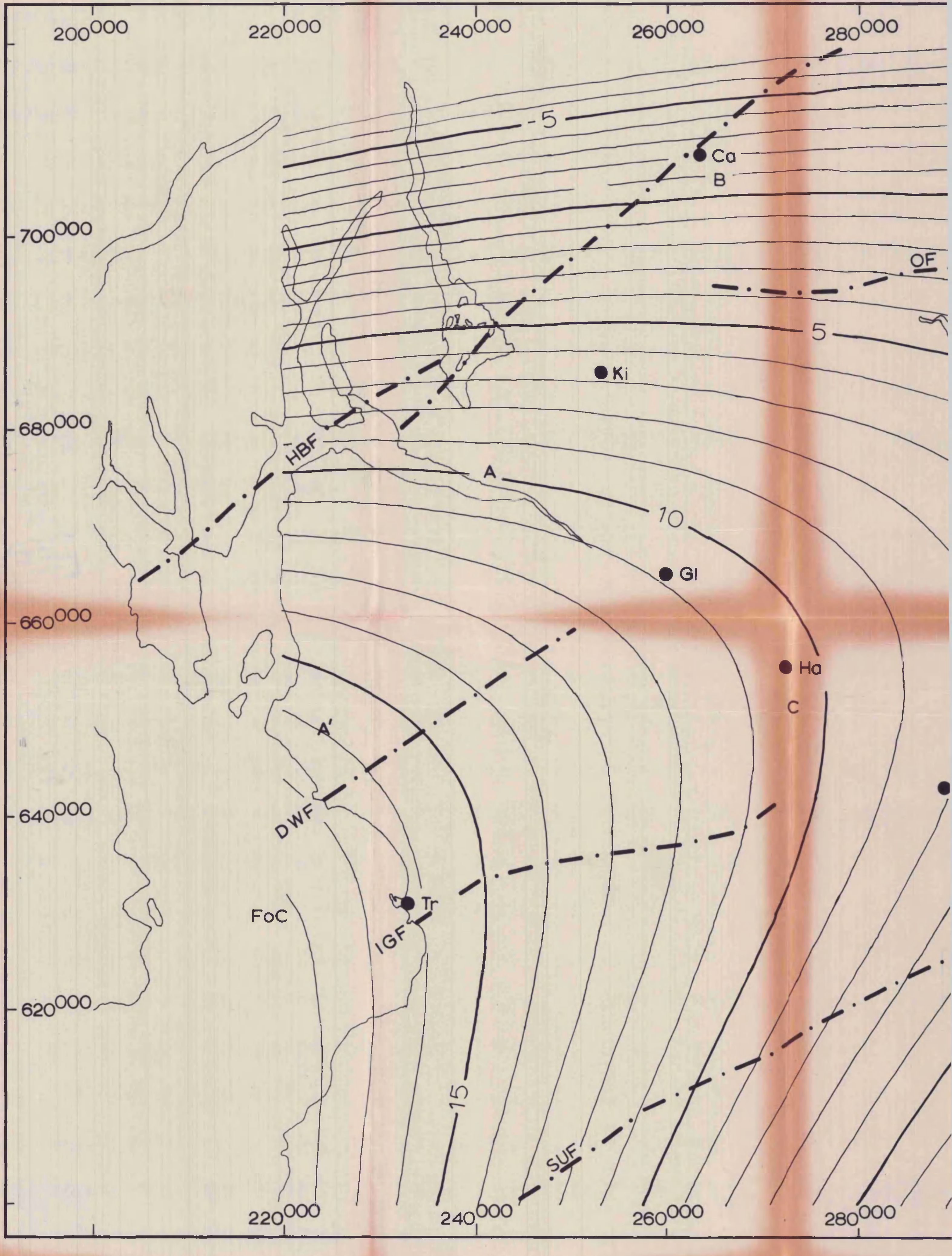

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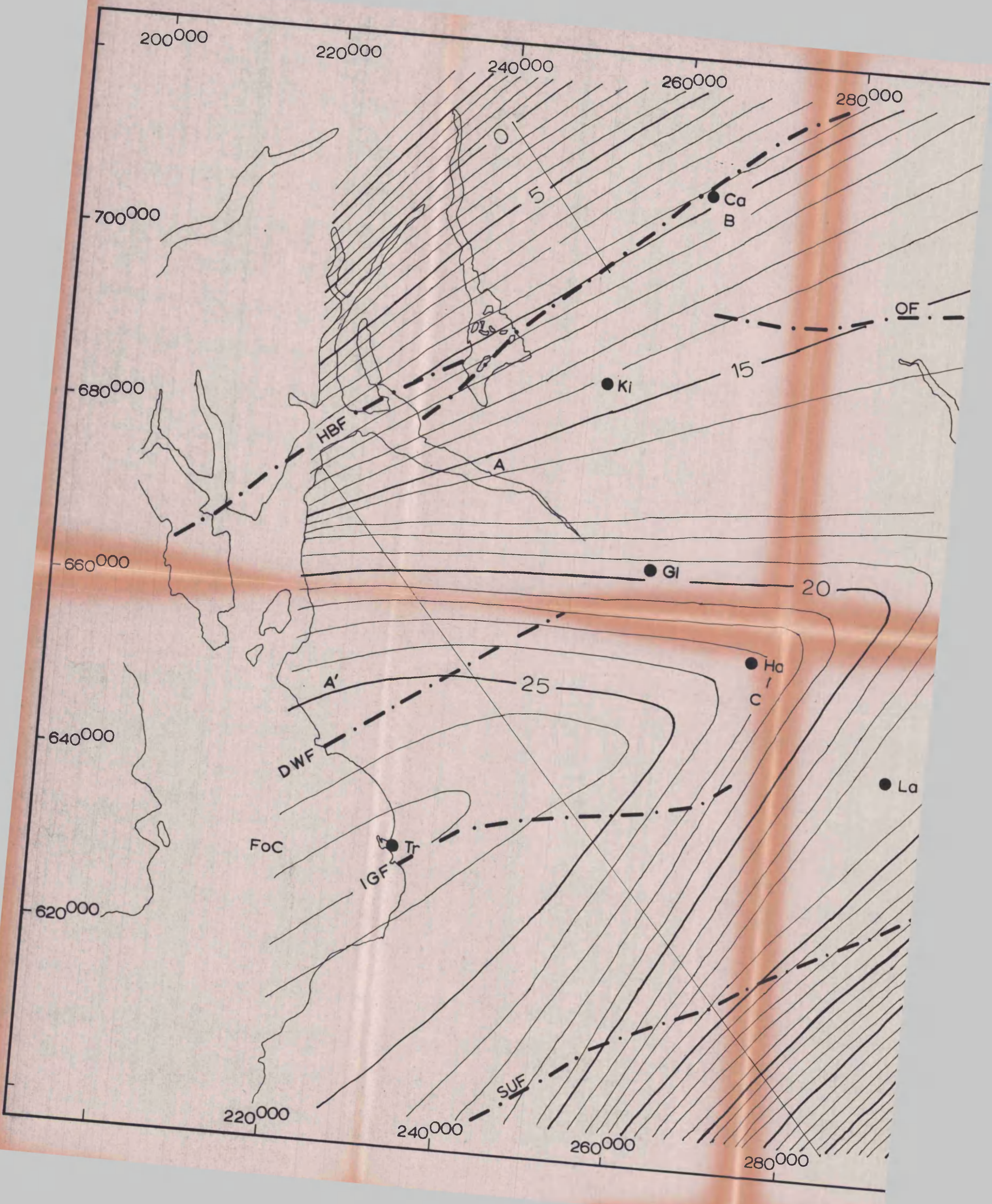

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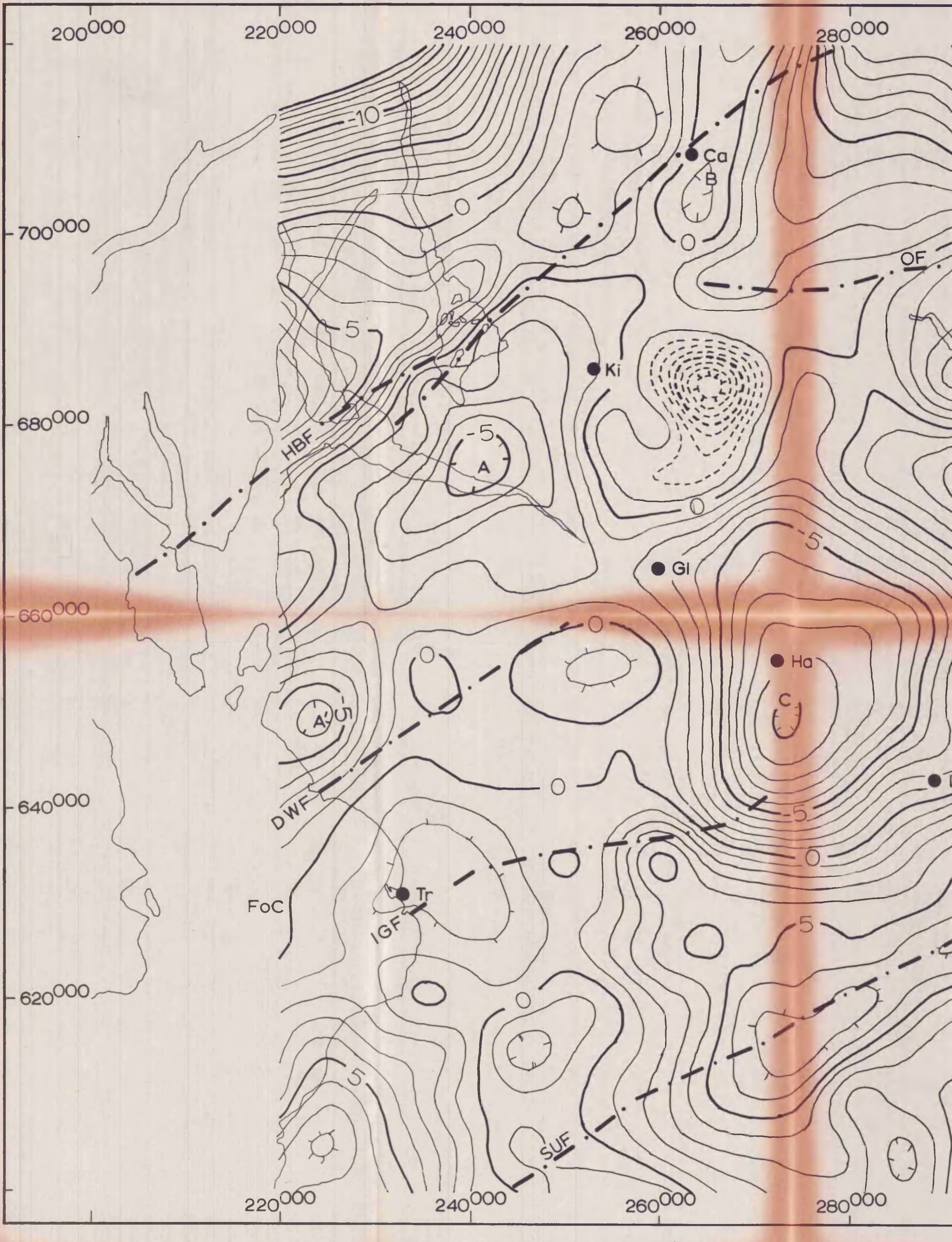

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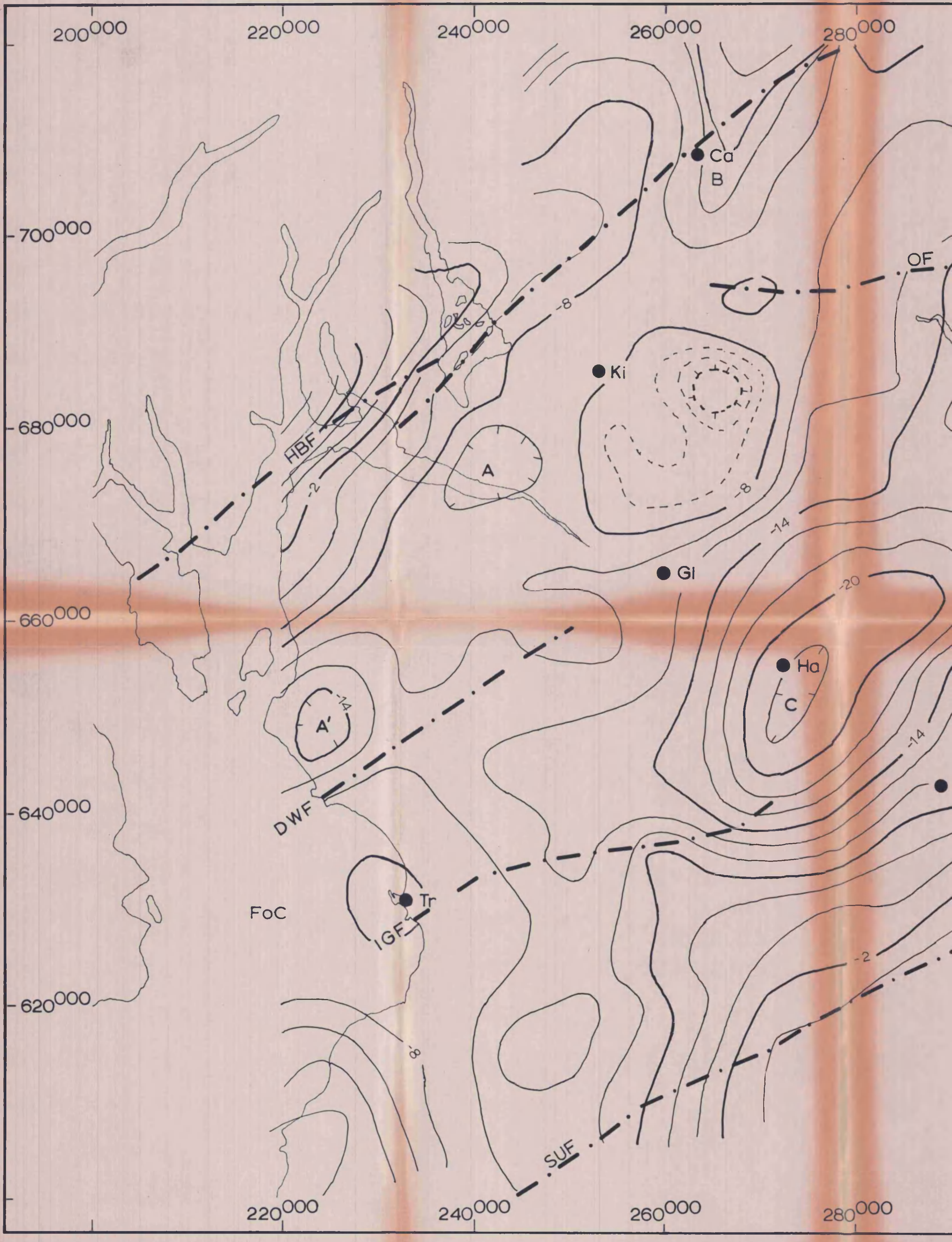

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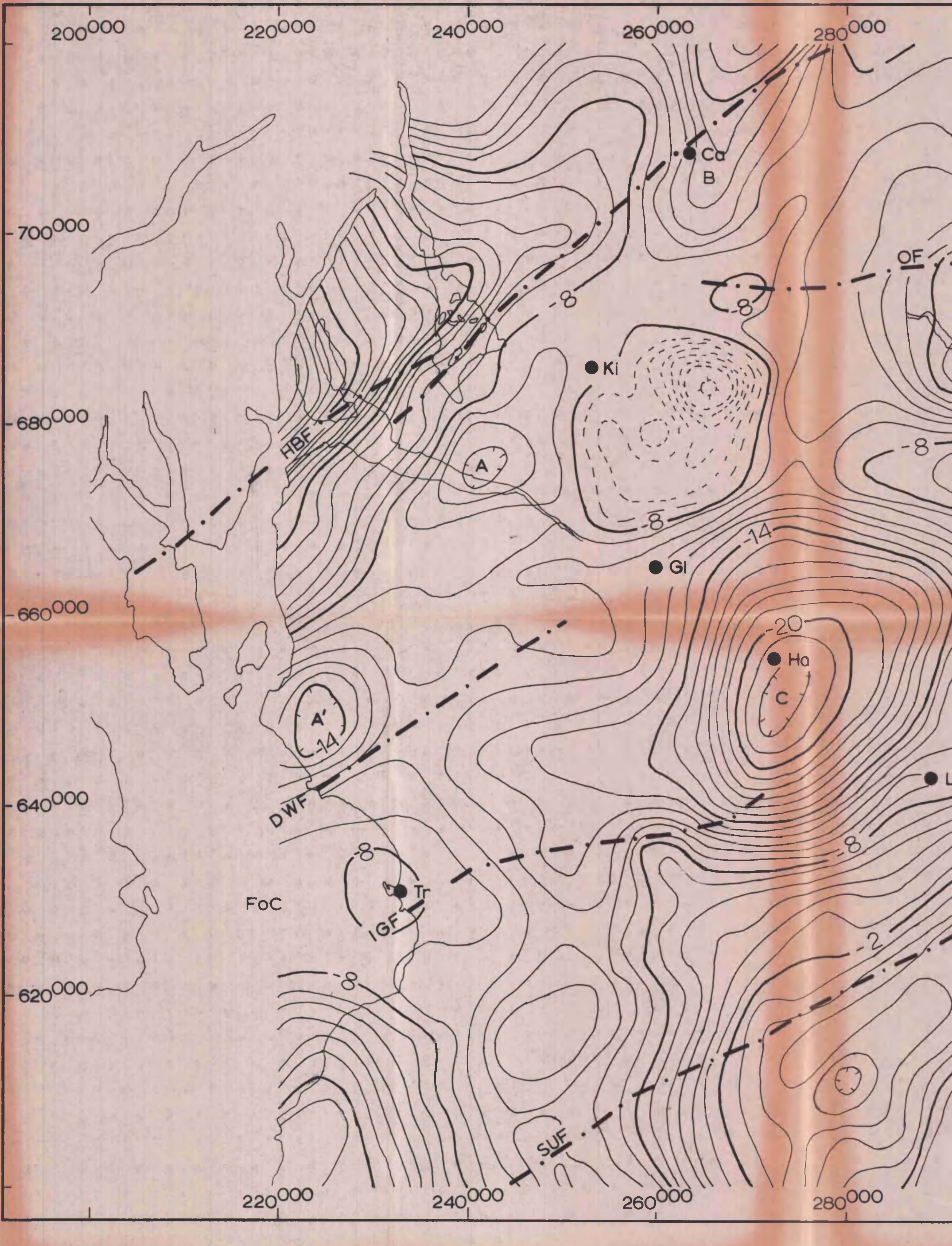
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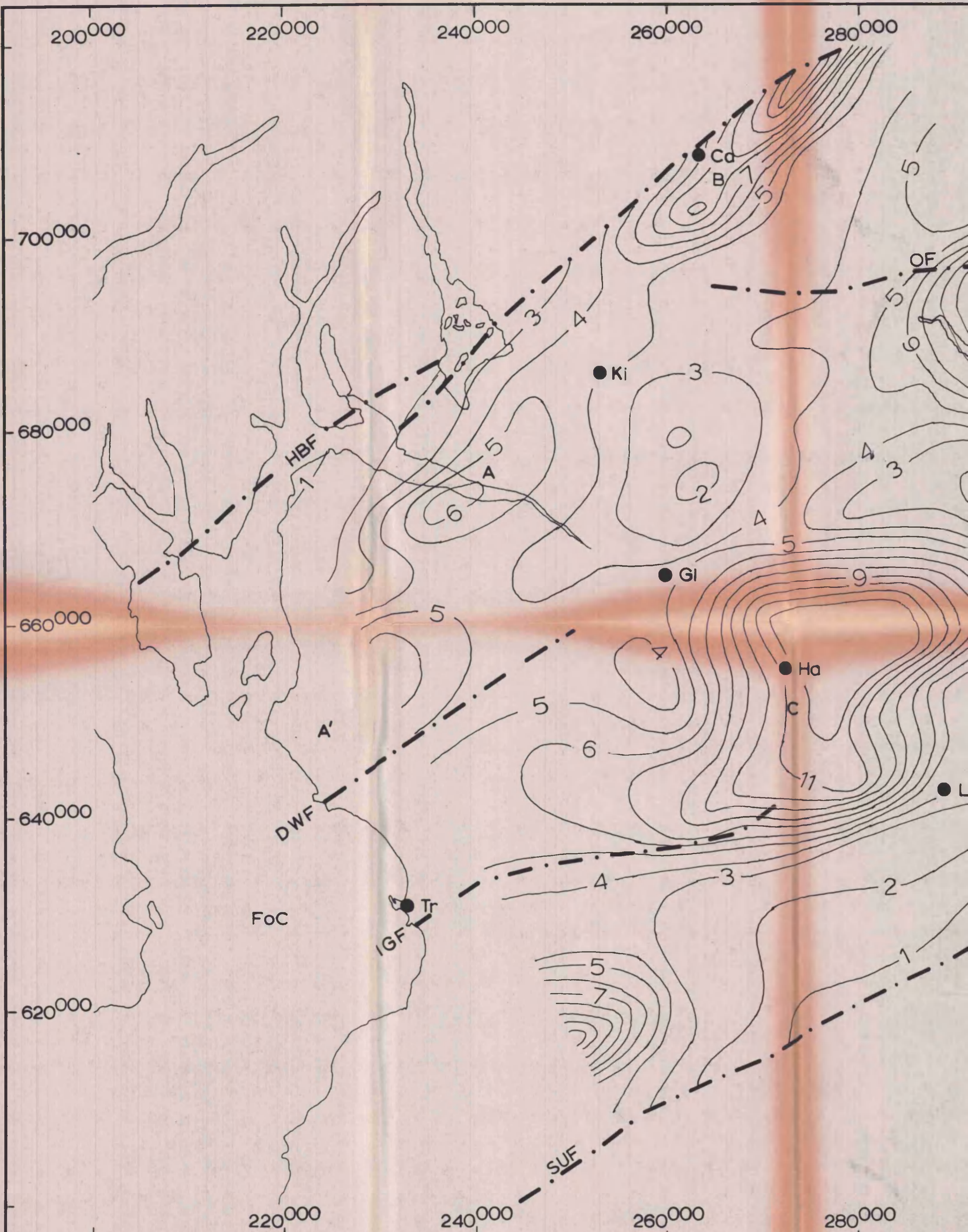

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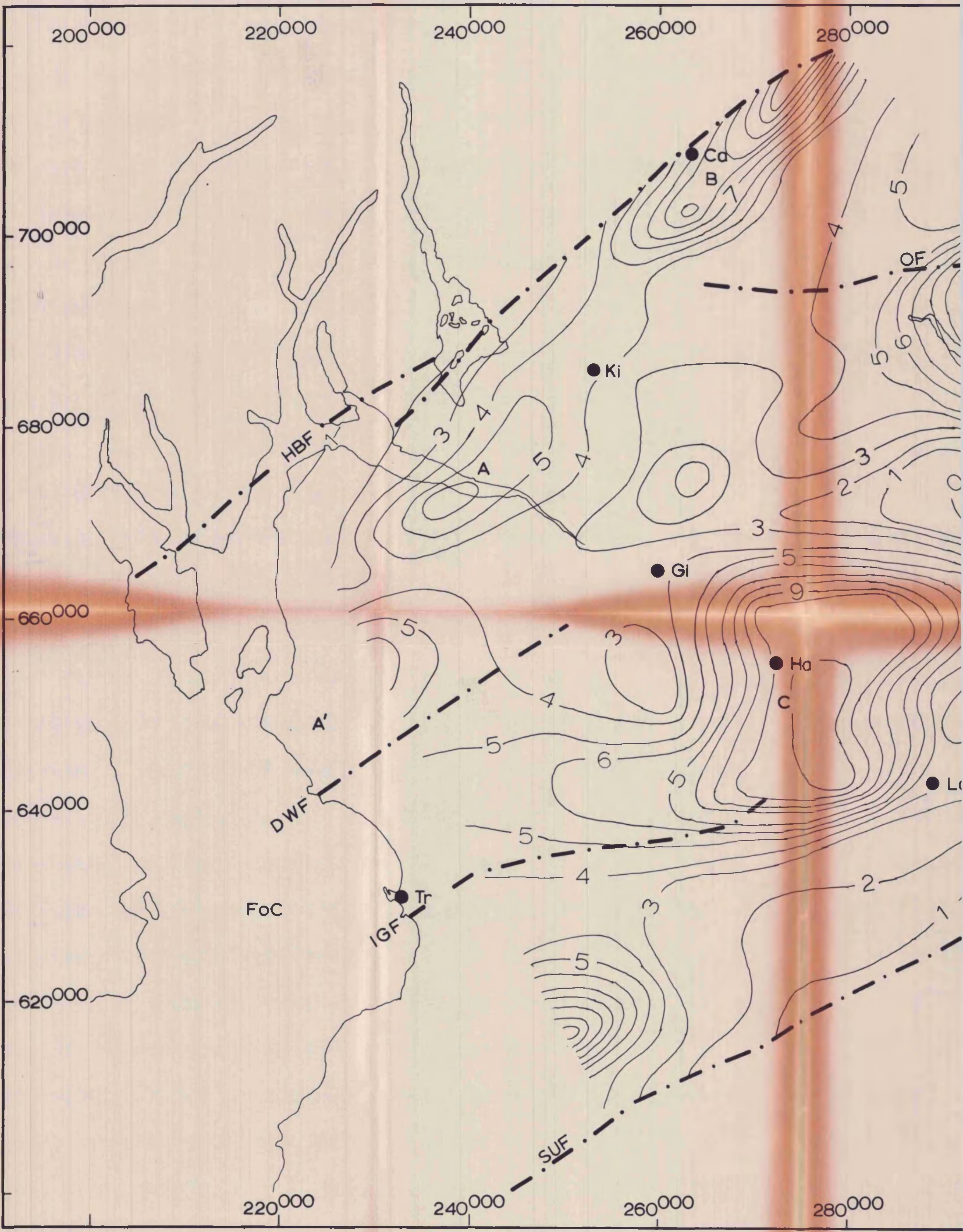

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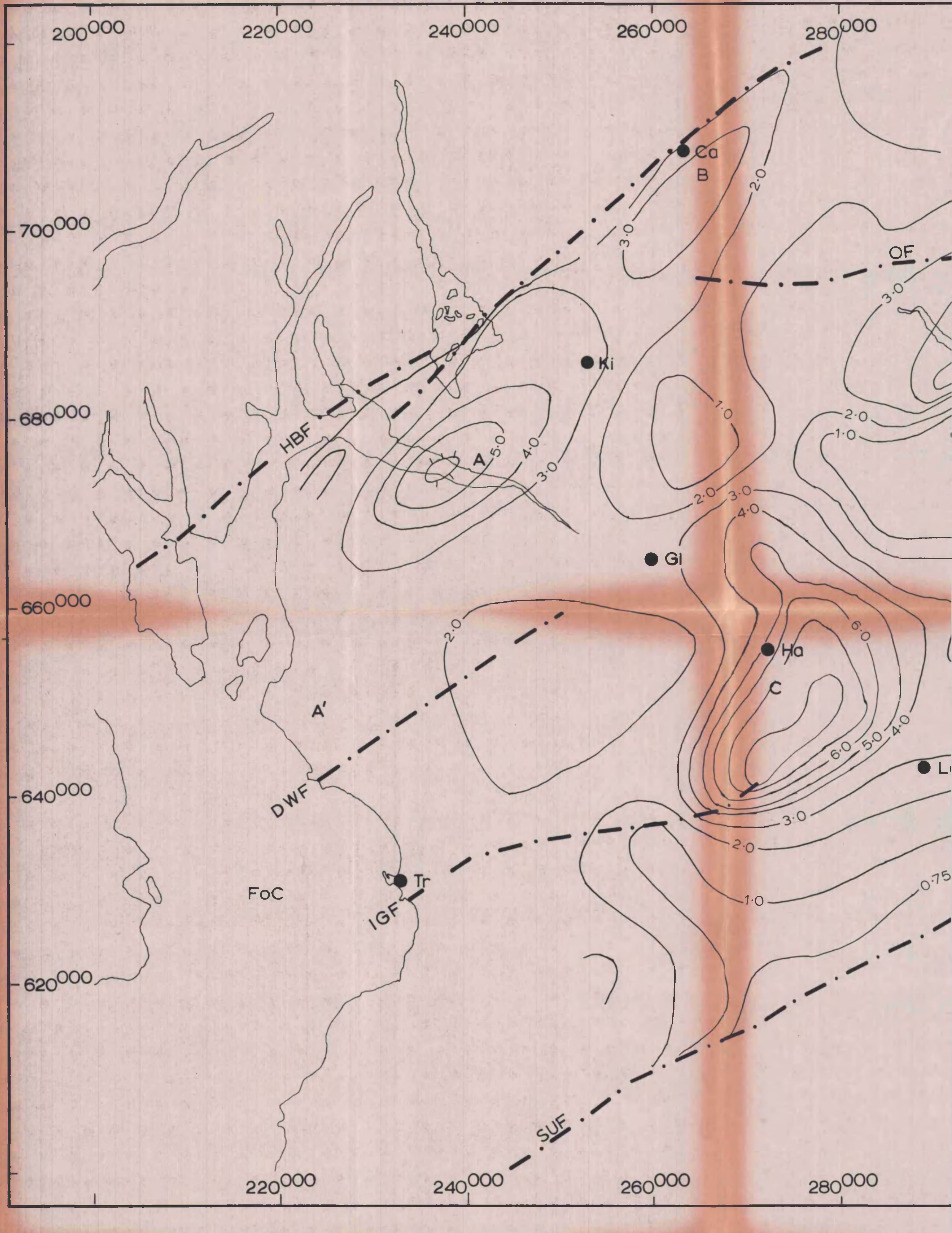

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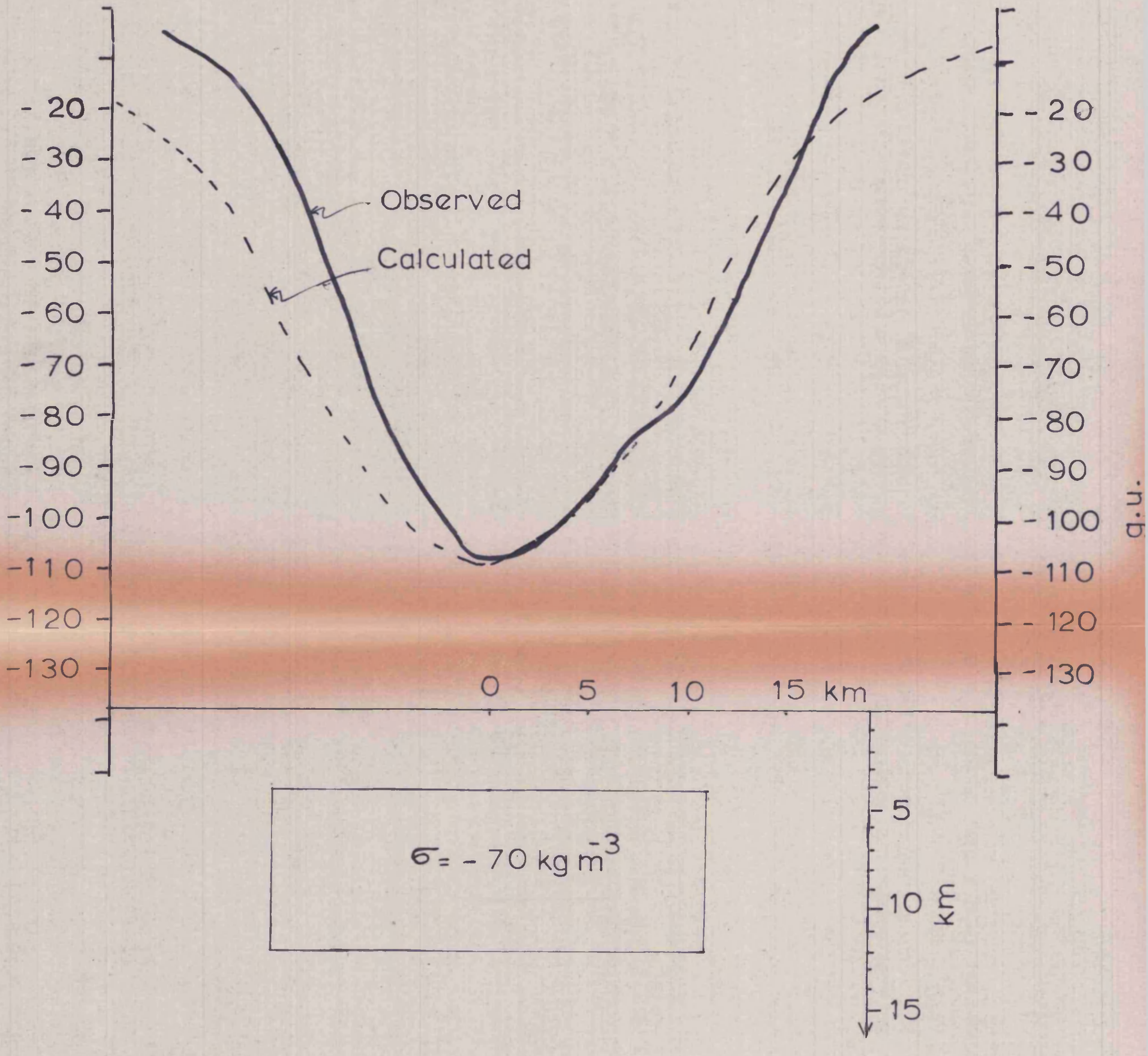
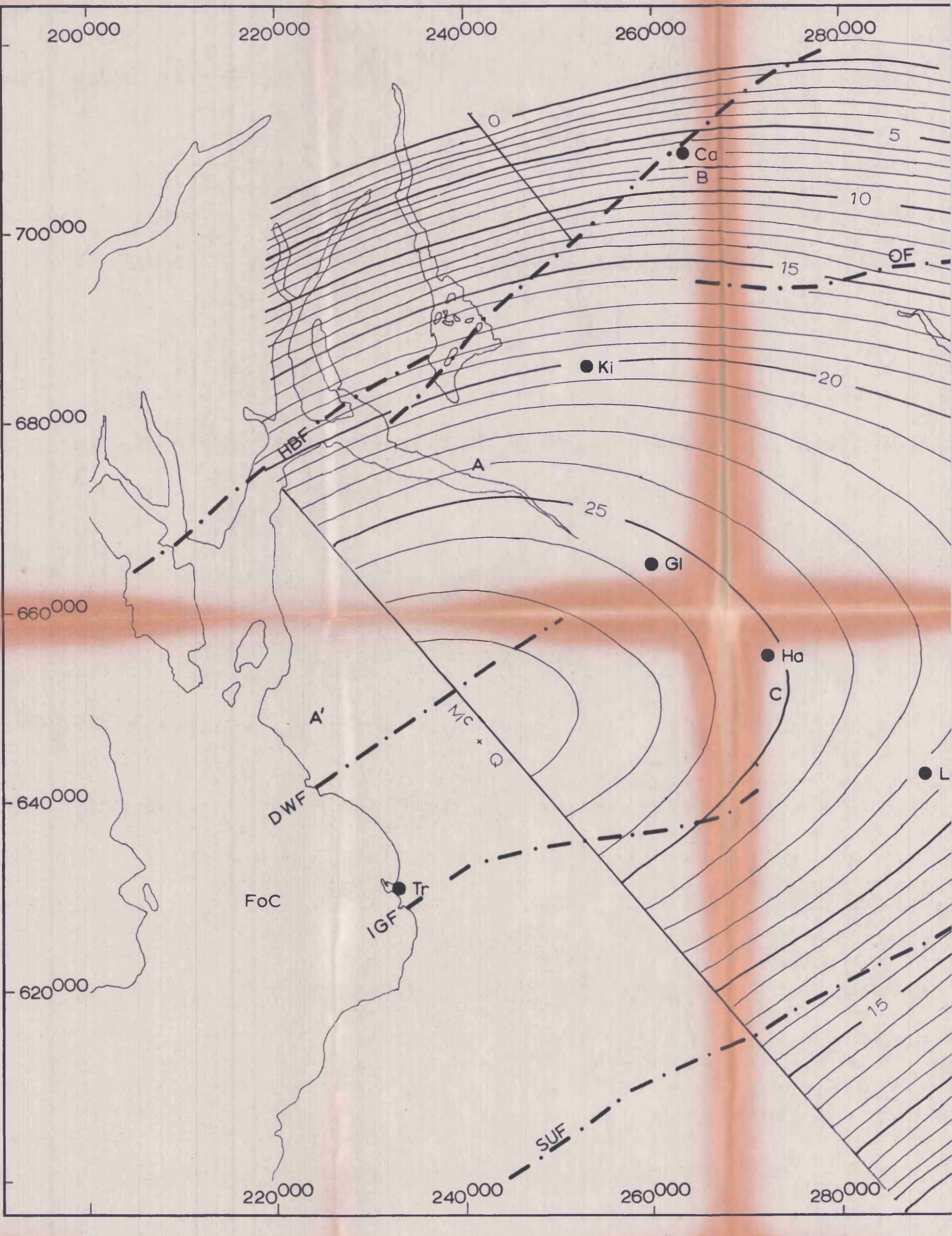


Fig. 26

CYLINDRICAL MODEL FOR LOW C



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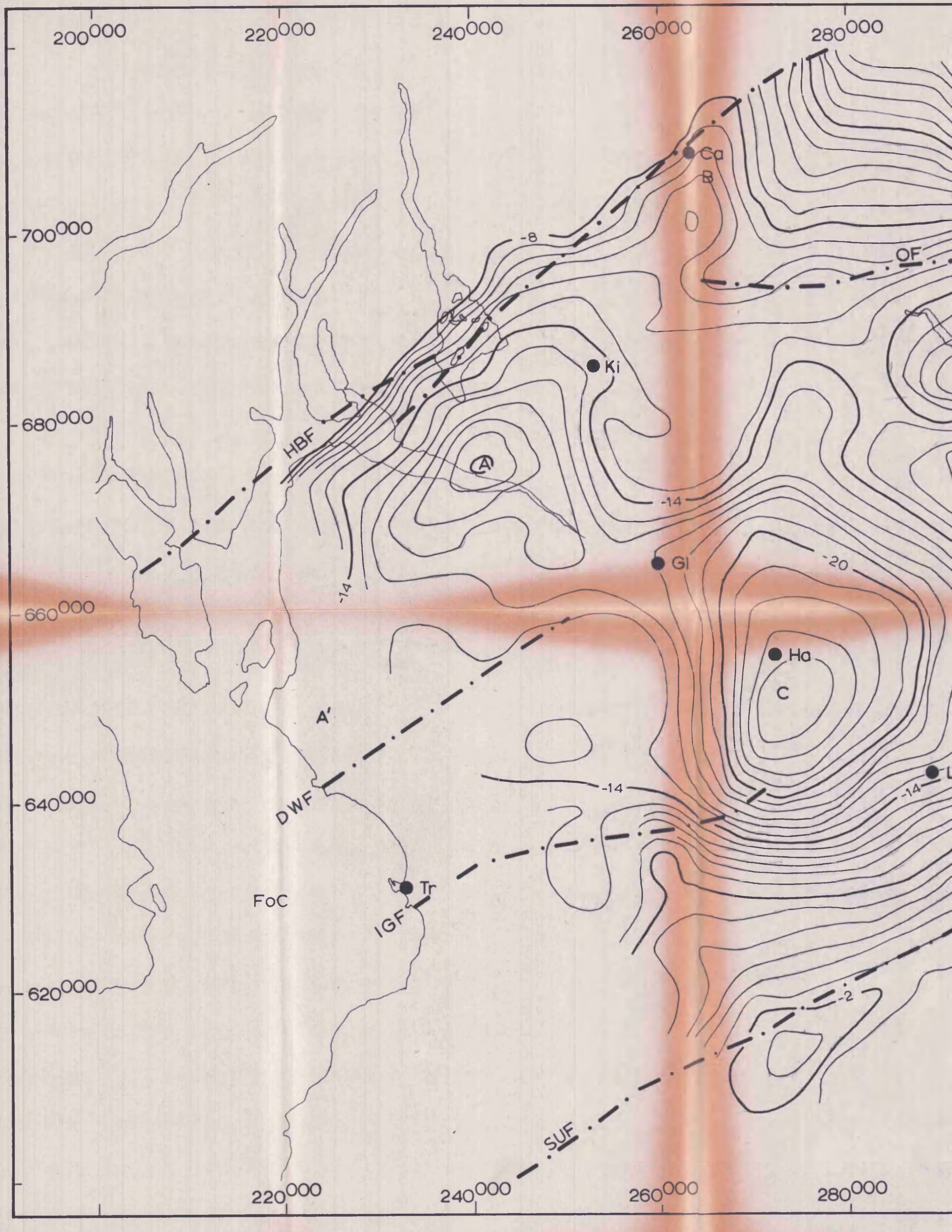
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Fig. 29 GRAVITY STATIONS IN THE MIDLAND VALLEY OF SCOTLAND 980 USED BY